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and the

Bulletin of the Society of Economic Geologists

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CRITICAL FACTORS IN FINDING HYPOGENE OREBODIES

W. JAMES BICHAN

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ABSTRACT

Ore search is best begun within those areas where lineal elements of the regional structure intersect known tectonic belts. The further factors pre-disposing towards the formation of orebodies include conditioning elements of geological, mechanical, physical, and chemical origin.

In discussion of these features it has been found convenient to group them under the headings of differential competency (due to geological conditioning); fracturing, fissuring to provide access channelways, tensional dilation and redistribution of values (all caused in response to the mechanical effects of crustal deformation); and thermal conditioning (embracing physical factors alone, or those of a physico-chemical nature). To these have been added the critical element of *timing*.

The majority of Canadian ore deposits exhibit more than half of the attributes considered essential to the ore environment. Aside from luck, a study of these features is a pre-requisite for efficiency and success in an exploratory venture.

INTRODUCTION

ONE of the more concrete goals of economic geologists is the discovery of ore bodies. This is reflected in the Fiftieth Anniversary Volume (1) in contributions by H. E. McKinstry (2), G. M. Schwartz (3) and F. S. Turneaure (4). A comprehensive review of all those factors that have had an important bearing upon the exact localization of ore would have been welcome. A survey of formerly accepted (and as often discarded) guides to ore (why ore is where it is) would have been no less interesting than useful from the historic standpoint. Such a study is a worthy research project. Lacking the library facilities at present, I shall not attempt to fill the gap. This paper is an attempt to present the fundamentals predisposing to the formation of ore bodies, briefly, and in so far as they have impressed the author. It is to be hoped that it may serve as a spur to further discussions in the Journal.

While there is no lack of illustrative material from all parts of the globe, no apology is made for drawing mainly upon Canadian material. The statistical summary is based upon published descriptions of Canadian deposits in the Structural Volume of the Canadian Institute of Mining and Metallurgy (6), and these figures serve as a preliminary assessment of the relative importance currently attached to the different factors.

REGIONAL CONCEPTS

This paper is not so much concerned with metalliferous provinces or with mineral belts. This phase of the subject was covered by F. S. Turneaure (4), who has highlighted those features of continental geology to which attention should be directed when making a choice of *areas* for more detailed exploratory effort.

The "orogenic belts" of Turneaure (4, p. 86), Billingsley and Locke (5), correspond with the "orogenic trends" of McKinstry (2, p. 217). Igneous activity and related hypogene mineralization have been identified at the intersection of these global axes with "transverse elements" (4, p. 87) from the time of Spurr (8) to the "major structural lineaments" of McKinstry (2, p. 217). These are the nodes about which our more intensive prospecting activities have become concentrated in recent years. The mineralized zones within which ore bodies are ultimately discovered are generally thought to be within their vicinity.

The tectonic belts are those sections of the crust whose geologic history has been most disturbed, and wherein all manner of forces have been given full play, such that certain combinations of them have been effective in the deposition of valuable mineral concentrations. It is because of the involved and complicated history of these crustal regions that our opportunities are so much better for finding within them the effective operation of other factors pre-disposing to ore formation.

What this paper will attempt to emphasize are the characteristics of prime interest to the prospector within those chosen areas of optimum disturbance that occur at irregular intervals along the tectonic axes. The immediate task is thus to pinpoint orebodies within regional structural elements that have

already been mapped, or are susceptible of being mapped by the geologist. Proof may already exist that some of these mineral fields do contain ore. Others will be examined because of the *suspicion*, based upon good and sufficient analogy, that they *may* contain ore.

Search efforts may be further systematized and localized within mineralized areas (i.e., those showing at least a disseminated mineralization) through such means as those mentioned by Schwartz (3), i.e., upon the basis of selective, or more intensive hydrothermal alteration. This is one of the more useful techniques and affords particular opportunities for much more detailed study in conjunction with the question: what is the optimum thermal environment for ore deposition in any given area?

Important as is the study of hydrothermal effects, Schwartz (3, p. 319) is the first to admit of its limitations when applied alone and lacking conjunction with other geologic features of the ore environment: "There are large areas of alteration that do not have ores, and there are ores where the alteration is weak." The fact is that hydrothermal alteration is almost regional in extent, as may also be true of some other factors (such as fracturing) that will be mentioned later. The hydrothermal effect is localized by geologic structures in proximity to igneous activity, and it can be graded, classified, correlated and mapped satisfactorily throughout any chosen area.

Hydrothermal alteration also provides an important clue to those portions of the disturbed orogenic zones that have undergone the most intense, or at the very least, a thoroughly adequate pre-mineralization conditioning of a physico-chemical nature. The subsequent arrival of the ore-bearing fluids thus finds the hydrothermally affected portions of the zones at temperatures, and to an extent in a preferred physical condition, appropriate to the orderly precipitation of the ore minerals.

Consideration of the role of hydrothermal alteration serves to highlight the entire approach to ore genesis. This type of change is evidence of physico-chemical conditioning of the highest grade. It may occur as a contact metamorphic effect, or may be of planar extent along the access channelways that are subsequently the routes followed by the ore-bearing solutions. The whole process is a modified thermal effect to which chemical reactions have been added.

The nature and extent of the pre-mineralization processes, as well as their intensity, determines whether we shall find ore, what kind of ore it will be, and in what quantities.

Environmental conditioning factors that have been effective in converting portions of a rock mass into blocks of host-rock may be primarily geological, mechanical, physical or chemical in origin. Geological conditioning decides the rock types present, as well as their general relationships, i.e., a sedimentary sequence will not provide the same host environment as a metamorphic or an igneous suite. Mechanical conditioning has been discussed very fully by McKinstry (2, p. 172–186 incl.) as a fundamental introduction to the structure of the ore deposits with which we are concerned. Physical conditioning includes all those aspects of environmental temperature, no matter how they have been derived; and chemical conditioning involves the formation of new

mineral combinations through the action of pre-ore fluids upon the host-rock, and of contact-metamorphic effects.

Inasmuch as the reaction of the host rocks to mechanical conditioning factors depend upon the physical properties of the rocks concerned, the diverse results of geological conditioning are to be considered under the heading of differential competency. A diversity of rock types, while not indispensable, is a factor pre-disposing to the more effective operation of mechanical conditioning factors, and its implications are therefore given first consideration.

Mechanical conditioning is primary, in the sense that extensive physico-chemical conditioning is impossible without it. Through mechanical conditioning alone can the ore-bearing fluids, as well as the pre-ore conditioning fluids, gain access to, and come into intimate contact with the host environment. For these reasons, the mechanical conditioning effects have been broken down into a number of categories: fracturing, i.e. the provision of host-cavities for the ore minerals; fissuring to provide access channels for the pre-ore and ore-bearing fluids; tensional dilation to permit the passage of the solutions along the channelways and their entry into the host-fractures; and repeated fissuring and reorientation of stresses to promote a redistribution of successive mineral fractions. The critical question of the timing of the elements of the mechanical conditioning process is given separate consideration.

Physical conditioning (i.e., the thermal effect) may occur with or without accompanying chemical reactions. It is convenient, therefore, to discuss thermal conditioning, as if it were a primary factor, and to interpret it according to heat source and other concurrent factors. Thermal conditioning alone occurs due to the proximity of a relatively late intrusive mass or dike. The temperature of the environment is raised without other noticeable effect. Limited chemical reactions may take place due to passage of solutions along channelways, through fracture zones, up the plunge of drag folds, &c. Elevation of temperature adjacent to an igneous intrusive may be accompanied by wholesale contact metamorphic changes and mineralization. Formation of fracture patterns *within* a cooling igneous mass may provide the two factors of cavity-formation and a relatively warm environment in convenient relationship to the still fluid magma below, to the extent that chemical changes during the later stages of igneous emplacement may be most marked.

The relevant factors have therefore been discussed under the following headings:

(1) *differential competency* in its broader aspects, and as a cause of orientational variations of fracture planes or systems;
(2) degree and extent of *fracturing;*
(3) propinquity of *access channels,* formed through fissuring or shearing, and in part by drag folding;
(4) *tensional dilation* to permit of the selective penetration of localized zones by the pre-mineralization conditioning fluids and later by the ore-bearing solutions;
(5) *thermal conditioning,* unaided by other factors, or aided by chemical reactions outside the igneous source, and within the igneous mass;

(6) *redistribution* of valuable mineral content;
(7) in general, the critical factor of *timing* of the onset of regional forces.

Differential Competency.—The significance of an assemblage of rocks of varying competency may be appreciated through a comparison of the type of fracturing that may be expected in such an environment. Fracture systems within an inhomogeneous and anisotropic host mass are susceptible to a greater degree of tensional dilation than those existing in a thoroughly homogeneous and uniform rock sequence. Rock masses thought to be consistent in their physical properties throughout, often show unexpected variations that may in turn contribute to the preparation of an ore environment.

The interfingering of rocks of varying competency produces the most suitable environment because the effects of the overall stresses are then localized within one rock type or another, and not dissipated throughout the formations. For example, the more brittle rocks will sustain tension fractures, whereas the incompetent rocks will not. Thus the effects of tensile stress are evident solely in the more competent members of the environment. Shearing stress, on the other hand, may be insufficient to rupture the more competent rocks, but finds its release only in the less competent beds through buckling, crumpling and attendant slippage along bedding, cleavage or contact planes.

Differences in competence at more elevated temperatures may be so marked as to produce flowage in certain rock types and fracture in others within the same temperature zone.

McKinstry (2, p. 180–184), in his study of fracturing, properly devotes space to the questions of inhomogeneity, non-uniform stress distribution, and to the importance of incompetent rocks being present in an ore environment. Uniformity of physical properties not only produces symmetrical patterns, but results in a relatively minor scale of fracturing, widespread in nature, and distributed evenly throughout the rock mass. Planes of weakness, such as bedding and cleavage, serve to control the fracture directions and their persistence. The "change of attitude on passing from one type of rock to another" is noted (2, p. 180), and is of major importance in explaining the changes in strike and dip of veins, as well as the changes in orientation of fracture directions in passing along the strike of interlayered formations.

The relative competency of varying rock types plays a major part in the localization of ore in the following percentages of cases (over 200) in the Structural Volume (6):

	Specific*	General	Total
Cordillera	12%	42%	57%
Shielf	7%	33%	40%
Overall	8%	35%	43%

* In which variations have been brought about in the altitude of veins or the orientation of zones of fracturing.

Recognition of the importance of the factor of *differential* competency is not as widespread as is its *existence*. Orientational variations have been recognized at Spud Valley, B. C., Surf Inlet and Pugsley, B. C., Eldorado, N.W. Territories, Red Lake, Ont., Bankfield and Tombill, Ont. Falconbridge, Ont., Matatchewan, Ont., Wasa Lake and Stadacona, N.W. Que., and in the Cadillac belt, Que.

The importance of differential competence has been stated in a number of cases from the Structural Volume:

Stockwell, C. H., and Harrison, J. M. (6, p. 286) Manitoba region
"Most of the orebodies occur on the limbs of folds where shearing and fracturing along or near contacts between competent and incompetent formations have taken place."

Stockwell, C. H., and Harrison, J. M. (6, p. 287) Flin Flon, Man.
"The Flin Flon orebodies are associated with quartz porphyry that occurs . . . along a contact between . . . competent basic lava flows . . . and more easily sheared fragmental volcanic rocks."

Stockwell, C. H. (6, p. 310) Central Manitoba mine
"the veins lie chiefly in a narrow bed of sheared tuff that is an incompetent formation between andesite to the south and sills of gabbro and diorite to the north."

Horwood, H. C. (6, p. 327) Red Lake field, N.W. Ont.
"The type of rock acting as a host . . . is dependent on its size, shape, position and physical characteristics relative to other neighbouring formations of different characteristics."

Horwood, H. C. (6, p. 344) Howey and Hasaga mines, N.W. Ont.
"The diorite is the least competent rock, for it sheared readily under stress. The porphyry is the most competent because it yielded only by fracture. The breccia is intermediate. Where the porphyry dyke has diorite close to or along its contacts the stress applied to the assemblage was taken up principally by shearing in the diorite. Where good widths of breccia enclose the dyke, however, the breccia yielded less readily and more stress was taken up by fracturing in the porphyry."

Matheson, A. F. (6, p. 411) Hard Rock mine, N.W. Ont.
"All the ore . . . is either along a contact that provided easy access or within a fractured, competent, brittle rock as opposed to adjacent incompetent rocks."

Dunbar, W. R. (6, p. 452) Hollinger mine, Ont.
"The different competency of rocks, such as where tuffaceous beds occur between flows, has influenced the direction and frequency of the fracturing. . . ."

Carter, O. F. (6, p. 502) Coniaurum mine, Ont.
"The formation of suitable openings appears to be a function of the relative competency of adjacent flow horizons. . . ."

Holmes, T. C. (6, p. 546) Dome mine, Ont.
"in the area of the mine the irregular distribution of rocks of varying competence would cause relatively sharp local changes in stress, which created conditions suitable for ore deposition."

Parsons, G. E. (6, p. 657) Bidgood mine, Ont.
"The soft, sheared condition of the diorite in contrast with the brittle, hard, massive dyke appears to have made the part of the fracture in diorite more open near the dyke."

Thomson, J. E. (6, p. 661) Omega mine, Ont.
"Movements along these shear zones would tend to shatter the harder, more competent lavas and cause rock flowage or shearing along the bedding planes of the softer tuffs, especially the slaty varieties. Under such circumstances the lavas would contain fractures and openings that would allow the circulation of the ore-bearing solutions and would become the locus of sulphide replace-

ment with attendant gold deposition. The tuffs, on the other hand, would be unfavourable, for they could not maintain fractures."

Wilson, M. E. (6, p. 780) Stadacona mine, Ont.

"The occurrence of ore . . . is obviously related to the change in structural competence from agglomerate, tuff, and andesite to massive diorite."

Fracturing.—The "shattered condition of great masses of rock" (2, p. 170) may predispose to an economic mineralization, but it is as nothing without other factors. The diversity of rock types of varying competence is well shown in the majority of McKinstry's illustrations (Figs. 1, 4–8 incl., 11, 12, 14, and 16–18, incl.).

Fracturing is placed second in importance simply because the diverse nature of the rock environment may often be determined through careful ground mapping, and is frequently suggested by aerial geophysical reconnaissance. Zones of adequate fracturing are, due to their highly broken state, and unless strongly resealed and recemented with resistant minerals, more easily worn away and concealed by drift or alluvium. This condition is comparable with that noted by Schwartz in regard to hydrothermal alteration: "It is evident that very narrow zones of alteration are of limited help in searching for ore because finding the altered rock is about as difficult as finding the ore."

The tie-in between mineralization-fracturing-erosional lows is nowhere more obvious than in the Canadian Precambrian shield areas. It is now a commonplace to expect that the major orebodies are beneath lakes or muskegs, since the clue to so many major mines has been at outcrops marginal to these topographic features, or as minor exposures surrounded by them.

Fracture patterns have been given adequate treatment by McKinstry, such that it should occasion no surprise to find the following percentages of Canadian deposits in which fracturing is acknowledged to play a leading part: Cordillera, 66%; Shield, 40%; Overall, 52%.

Where fracture zones have been unimportant in localizing the orebodies, it has been because the mineralization has been confined to the faults or shears that provided access for the ore-forming fluids. If these larger fissures (or fractures) be included with fracture systems as loci for ore, then the overall figure for Canada becomes 92 percent. The only exceptions are a few examples of peripheral segregation of massive sulphides in association with igneous masses.

Fracturing is clearly of such fundamental importance that no useful purpose could be served in listing Canadian examples: virtually all of those epigenetic deposits described in the Canadian Institute of Mining's Structural Volume owe their economic importance in the first instance to the ever-essential pattern of fracturing within the host environment. Their commercial sections highlight the controlling effect exercised by other factors yet to be discussed.

Fracturing, unlike hydrothermal alteration, is a pre-requisite for ore in many mineral provinces; like the hydrothermal effect, it may also be present on a large scale, and in fact is almost universal, *without* any associated ore deposits.

Access Channels.—The necessity for access channelways in the form of zones of shearing or regional faults appears inescapable so long as it is inferred that the prime source of ore-forming solutions is juvenile. Permeable beds have been invoked (2, p. 173), and it would be quite possible for these to be adequate to tap the mineralizing reservoir, just as the splitting apart along formational contacts or cleavage planes could do so if there existed a considerable vertical range to the fold structures. Through-going shears, normal and reverse faults have been recognized and noted in 65 percent of all Canadian deposits by a wide range of authors. The "necessity for channelways" is not unnaturally clearly recognized by McKinstry (2, p. 173). Channelways may not always be easy to identify as such when they are neither mineralized nor the locus of hydrothermal or associated types of alteration. The passage of ore-bearing fluids may have been followed by a reorientation of stress that has brought about a tight closure of the original fissures.

The role of channelways in the process of economic mineralization may be summarized through a number of references from the C. I. M. Structural Volume (6):

Armstrong, J. E. (6, p. 140) Pinchi lake mine, B. C.
"In most of the mercury deposits it is apparent that the Pinchi fault zone provided abundant channelways for mineralizing solutions."
Benedict, P. C. (6, p. 159) Island Mountain mine, B. C.
"the Aurum fault was an important trunk channel for solutions."
Richards, F. (6, p. 165) Cariboo Gold Quartz mine, B. C.
"the faults provided channels for the ore-bearing solutions"
Lord, C. S. (6, p. 199) Regal Silver mine, B. C.
"shear zones . . . provided the channelways for solutions that deposited the quartz vein-filling."
Brown, W. L. (6, p. 237) Monarch mine, B. C.
"the intersection of the two major shear zones . . . provided a major channelway for solutions to migrate laterally."
Henderson, J. F. (6, p. 241) Negus and Rycon mines, N.W. Territories
"well-defined quartz veins introduced along shear zones"
Stockwell, C. H. (6, p. 310) Central Manitoba mine
"The two faults that border the wedge-shaped block of ground are wider shear zones containing a little gold. They may have served as channelways for the solutions that deposited the ore."
Moore, E. S. (6, p. 417) Michipicoten-Goudreau area, Ont.
"It is probable that the lack of major faulting about the time the gold was being deposited explains why, in so far as the search has been carried on, no large deposits have been found in the area."
Bartley, M. W. (6, p. 420) Steep Rock mine, Ont.
"The faulting and shearing provided the channels through which the solutions . . . percolated"
Yates, A. B. (6, p. 608) Sudbury, Ont.
"The structures that have provided channelways for mineral-bearing solutions and for the ore are faults."
Buffam, B. S. W. (6, p. 668) Chesterville mine, Ont.
"It was along . . . sheared zones that alteration was concentrated and that the gold-bearing solutions travelled."
Brown, W. L. (6, p. 692) Normetal mine, N.W. Quebec
"Faults intersecting these fractures would act as subsidiary channelways and guide sulphide solutions to favourable horizons."

Hawley, J. E. (6, p. 728) Aldermac mine, N.W. Que.
"the mineralization . . . consisted of the early introduction of pyrite and quartz along steeply dipping faults."
Mills, J. W. (6, p. 808) Mic Mac mine, N.W. Que.
"The juxtaposition of the shear zone and the orebodies and, more especially, the presence of a similar mineralization within the shear zone points to the shear zone as the channelway for the mineralizing solutions or vapours."
Wilson, H. S. (6, p. 890) Lamaque mine, Que.
"the faulting . . . that furnished channels for the circulation of the vein-forming solutions."

Tensional Dilation.—Dilation as a prime factor in the admission of ore-bearing solutions to any given environment has yet to be accorded its due importance. The dilational mechanism through which space is derived through the operation of tensile stress within the fracture pattern has not been elaborated by McKinstry (2, p. 174), who recognizes that such space can be produced without the operation of either of the other two methods he mentions: solution and metasomatism.

Tensional dilation has so obviously occurred in so many ore environments, and incidentally in many that do not constitute ore, such as monomineralic stockworks of quartz veinlets, that its denial is impossible. Canadian case histories, however, only include specific mention in the following ratio: Cordillera, 6%; Shield, 38%; Overall, 30%. Regarding the Eldorado orebodies at Great Bear Lake, N.W. Territories, R. Murphy (6, p. 265) holds that "everything suggests quiet and uninterrupted deposition in an opening probably produced by tension." J. D. Bateman (6, p. 283) considers that "the combination of deforming stress and the flexures of the shear zones resulted in high and low pressure areas." In the former, at the Giant Yellowknife gold mine, N.W. Territories, the fracturing remained tightly or nearly closed. Fractures in low pressure areas opened up by tensional dilation to receive the ore.

Perhaps the reason for the hitherto neglected treatment of so evident a feature as the dilation of veins and systems of fractures has been the further implied necessity to account for this dilation selectively in certain zones (commonly the ore bodies, or the ore shoots within the mineralized blocks), and the lack of it in nearby sections otherwise identically favorable, i.e., between the low pressure blocks (zones of tensional dilation) and those of high pressure (zones of compression).

Thermal Conditioning.—The significance of the environmental temperature within a zone of mineral deposition is this: in a relatively cool environment the initial paragenesis is the end product of the mineralization process; in an environment at a temperature not far below that of the mineralizing fluids there is afforded an opportunity for fractional precipitation. Successively enriched intermediate and ultimately end fluids may then be led off from the main channelways, or original zones of deposition, through reorientation of stresses, into nearby zones of tensional dilation either within or adjoining the vein channels to form higher grade ore shoots, or those with an unique mineralogy.

Lovering's study (7) of "Temperatures in and Near Intrusions" may well

serve as a starting point in the investigation of the optimum temperatures of the diverse ore environments.

Pre-heating of the environment due to igneous intrusion can be inferred to have been of importance to the following proportion of Canadian ore deposits: Cordillera, 38%; Shield, 51%; Overall, 48%.

Thermal conditioning may be due to:

(1) the host rock itself being the last previous intrusive in the area, and its cooling sequence being incomplete at the time of introduction of the ore minerals;
(2) proximity to a relatively late intrusive;
(3) passage of pre-mineral fluids at higher temperatures through the fracture zones and channelways.

The latest antecedent intrusive ahead of the mineralization process appears to be the host rock in the following mines and districts:

Surf Point and Edye Pass, the Red Rose tungsten-bearing vein, Hardie group cinnabar veins, Indin Lake, Laguna, Sherritt Gordon, Bobs Lake, Squall Lake, San Antonio, Howey, Hasaga, Sunbeam Kirkland, Red Lake Gold Shore, Pickle Crow No. 2. vein, Cline Lake, Renabie, Porcupine, Ross, Lake Geneva, Sudbury, Young-Davidson, Matachewan, Bidgood, Senator Rouyn, Simon Lake, Vinray, Elmas, Louvicourt Goldfields, Croinor, Sullivan, Perron, Beaufor, Siscoe, Buffadison, Bevcourt (Bevcon), Regcourt, Cournor, Pascalis, Formaque, Beacon, Indian Molybdenum, East Malartic, Malartic Goldfields, Central Zeballos, and the "porphyry" ore bodies at Sigma (6).

Worthy of note are these pointed comments by E. L. Bruce (6, p. 435):

"On the third level, the western end (of the Cline Lake mine's A vein), which is entirely in greenstone, contains only short lenses of ore. The eastern end where the vein is in granodiorite and felsite had a considerable length of good ore."

At the ensuing list of deposits, the ore bodies are sufficiently close to the nearest (and latest preceding) intrusives to suggest a strong controlling influence through the raise in temperature of the host-environment by these igneous masses: Tulsequah, Hidden Creek, Bridge River, Flin Flon, Pickle Crow No. 1 vein, MacLeod Cockshutt, Hard Rock, Bankfield, Tombill, Jellicoe, Michipicoten-Goudreau, Jerome, Normetal, Beattie, Arntfield, Wasa Powell-Rouyn, Waite Amulet, Quemont, Stadacona, Lamaque, Sigma, Norbenite, Shawkey, Quebec Provincial Mine School, Greene Stabell (Jacola), Harricana, New Bidlamaque, Canadian Malartic, Sladen Malartic, and Siscoe (6).

The ore bodies at the Sigma mine, N.W. Quebec, are either within or along the contacts of the latest antecedent suite of igneous dykes. The better-grade ore shoots are wholly within intrusive masses. The youngest dikes become ore where adequate tensional dilation has provided a high enough percentage of auriferous filling in the stock-work type of joint fracturing.

Particularly significant evidence is offered by W. P. Corking (6, p. 375):

"The hanging-wall of the (No. 1. vein at the Pickle Crow mine) is almost universally bordered by a fine-grained, basic dyke rock. As a rule the value of the ore decreases with the pinching and disappearance of this dyke rock. This feature

has, however, no apparent effect upon the vein itself" (i.e., only upon the gold content).

At the Beattie mine, N.W. Quebec, the syenite porphyry intrusive stock has been recognized by S. Davidson (6, p. 699) as a "hot centre" with a steep temperature gradient into the surrounding Keewatin series, and as being thereby responsible for the fact that "no ore has been found very far from the syenite or related lath-porphyry dykes."

The passage of high temperature fluids through the ore environment immediately prior to the appearance of the ore-bearing solutions may be inferred from the evident hydrothermal alteration zones at many properties whose host-rocks were already at an elevated temperature through proximity to igneous bodies.

The following are a few examples where the thermal conditioning has more plainly been brought about through the passage of hot fluids, unaided by proximity of the environment to an igneous source of heating: Privateer, Surf Inlet, Pugsley, Britannia, Pinchi Lake, Stump Lake, Copper Mountain, Sullivan, Giant Yellowknife, Con, Eldorado, Central Manitoba, Cochenour Willans, Berens River, Central Patricia, Delnite, Aunor, Porcupine Peninsular, Omega, Chesterville, Aumaque, Golden Manitou, Moulton Hill, and Kerr Addison (6).

The incidence of thermal conditioning, either as the sole factor in pre-heating the potential zone of ore deposition, or in conjunction with the physical influences of competence diversity attributable to surrounding or nearby intrusives is as follows: Cordillera, 18%; Shield, 23%; Overall, 22%.

The vital importance of pre-heating may be judged by adding the above percentages to those previously given for thermal conditioning due solely to igneous intrusion: Cordillera, 56%; Shield, 74%; Overall, 70%.

It is therefore considered that thermal conditioning should be ranked in importance with mechanical conditioning, although commonly dependent upon the latter. Mechanical conditioning alone can provide loci of deposition for minerals from whatever fluids may be available. Quartz and calcite veins, pegmatites, aplites, lamprophyres and other members of the minor intrusives suites are more likely to be the end result than deposits bearing shoots of metalliferous ores. Thermal conditioning in conjunction with mechanical conditioning, can prepare the environment in such a way that the processes of deposition from suitable solutions are long-continued through the slow cooling period of the thermally conditioned rocks. There is thus afforded a number of opportunities for a regrouping of the mineral products into shoots of ore as will be noted in the next section on redistribution of values.

The minerals of the hydrothermally conditioned zones discussed by Schwartz (3) are almost all present in some Canadian deposits. Chlorite and sericite are perhaps the ones that are universal. As the temperature of the host-rocks becomes raised towards that of the conditioning and mineralizing fluids, so the scale of reaction is increased when the two meet, and the more intense becomes the penetration of the wall rocks by hydrothermal alteration minerals, or by valuable metallic minerals, as the case may be.

Redistribution.—Subject to frequent note has been the fact that the mineralization and paragenesis within a vein or other deposit has rarely been the result of a single process, but rather does it consist of a number of stages, with tectonic movements intervening. The gradual precipitation of the vein-forming minerals, long-continued throughout the cooling period of the thermally conditioned environment, will permit migration of the still-fluid portions whenever a reorientation of stress takes place, and is relived by renewed fracturing and fissuring of the host-rocks.

The fluids remaining in the vein channelways and stockworks at an intermediate stage in the mineralization process cannot be identical with those present at the start of the ore-forming process. It is reasonable to state that, while they have become impoverished with regard to those minerals that have already begun to deposit, they will be enriched in the constituents of later crystallization, notably the metallic sulfides and the precious metals.

Migration of the metallic-enriched still-fluid fractions of the ore-depositing solutions within the zone of mineralization will carry them to new blocks undergoing tensional dilation. It is in these blocks that the preponderance of the metallic values will be deposited. Although it appears more likely that the fluids generally withdrawn are those that are enriched with regard to the valuable constituents, it is also possible that a withdrawal of gangue constituents might take place, and have the effect of enriching the portion of the ore zone that has already been deposited.

The concentration of the metallic values into shoots *within* the vein or zone of overall mineralization can thus be logically explained. Any mechanism that explains the *ore* must also be adequate to account for the sub-commercial metallic mineralization with which ore is almost invariably associated.

The study of redistribution has been insufficiently advanced for the production of statistics as to its importance. That it exists may be judged from the lateness of crystallization of the valuable minerals and by a number of references to the fractured state of ore shoots:

Murphy, R. (6, p. 264) Eldorado mine, N.W. Territories
"The segregation of the various metallic minerals separately in lenses in the vein is characteristic."

Mawdsley, J. B. (6, p. 339) Red Lake Gold Shore mine, Ont.
"Gold is present only in part of the vein quartz, and some of it at least is along fractures in the quartz . . . these late events were economically very important, as this fracturing resulted in passageways along which, among other things, gold-bearing solutions ascended, and in which the gold was deposited."

Horwood, H. C. (6, p. 349) Howey and Hasaga mines, Ont.
"The veins are made up of massive, white to grey quartz that, in places, has been fractured and mineralized with sulphides."
"The ore shoots are local developments where the vein quartz has been highly fractured and well mineralized."

Horwood, H. C. (6, p. 356) Cochenour Willans mine, Ont.
"After the fracturing, which was localized in the wider sections of the veins, later auriferous mineralization was concentrated in these sections to produce the best ore shoots."

Carter, O. F. (6, p. 501) Coniaurum mine, Ont.
"In most veins there is clear evidence that the original vein material has been refractured and intruded by a second age of quartz, . . . The gold content of

the veins of the first deposition is no less than that of the veins of the second deposition."

Longley, C. S. (6, p. 534) Paymaster mine, Ont.

"The zone includes the quartz-carbonate veins that have been re-fractured and enriched by later injections of gold-bearing solutions."

Wilson, H. S. (6, p. 891) Lamaque mine, Que.

"the veins . . . have been reopened a number of times, and it was with the vein material deposited following one of the later fracturings that the gold was introduced."

In the Noranda district it has been repeatedly noted that certain of the ore minerals characteristic of the massive sulfide bodies have penetrated as minute threads and seams the marginal fracturing in diabase dikes that are clearly later than the sulfide bodies and transgress them. A reasonable explanation is that the sulfide bodies had not completely cooled, or had not been completely precipitated when the diabase intrusion took place. Those fractions still fluid were enabled by their fluidity to penetrate the dike rock along its shattered margins.

Timing.—Evidence of the times at which vital movements along shear zones have occurred, of the periods during which certain portions of the mineralized zones have been in states of tensional dilation or compression, or of the later reopening of partially mineralized veins and stockworks, is most meagre. The elemental fact appears to be that all of these things have occurred, but the time schedule has rarely been worked out in detail. This may be due to the neglect of the aspect of an ore deposit that used to be termed its geologic history. Today this is often confined to the paragenesis of the ore minerals, and it is comparatively recently that recognition has been given to the pre-ore dating of the hydrothermal alteration in the wall rocks, formerly assigned to the ore-depositional phase.

The importance of timing has been recognized by those who have investigated a few of the Canadian deposits:

Murphy, R. (6, p. 268) Eldorado mine, N.W. Territories

"the tension fracture (No. 2. vein) must have opened during the invasion of the carbonate solutions. Not only did the fracturing occur at precisely the right time, but, also, in view of the grade of the vein, conditions must have been ideal for pitchblende deposition."

Jones, W. A. (6, p. 480) Hollinger mine, Ont.

"The textural and structural characteristics of the quartz veins bear witness that their formation was a long process. Many observers believe that the shear zones and other lines of weakness, developed during foldings and igneous intrusion, were later opened by much weaker, intermittent forces that permitted mineral solutions to penetrate the fractures. There is evidence of several periods of quartz deposition, each preceded by fracturing of the antecedent vein material. Forces that caused the fracturing appear to have become successively weaker and were localized in the existing vein channels."

The figures are as follows: Cordillera, 15%; Shield, 16%; Overall, 16%.

SUMMATION

Certain Canadian ore deposits exhibit all, or nearly all of the salient characteristics deemed essential to the occurrence of ore bodies. Examination of

TABLE 1

INCIDENCE OF FACTORS PRE-DISPOSING TOWARDS THE OCCURRENCE OF ORE IN CANADIAN DEPOSITS—1948 (6)

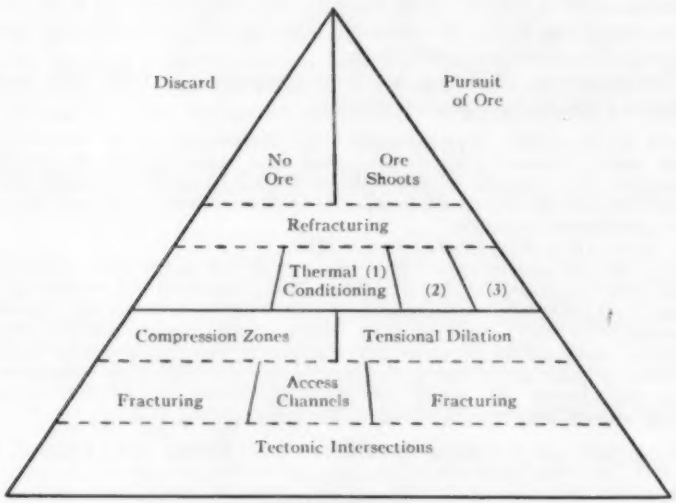
	Cordillera	Shield	Overall
Differential competency	57%	40%	43%
Fracturing	66%	40%	52%
Access channels	66%	65%	65%
Tensional dilation	6%	38%	30%
Thermal conditioning	56%	74%	70%
Redistribution of values		Under 1%	
Critical timing	15%	16%	16%

the descriptions in the Structural Volume (6) shows that the vein systems of the Eldorado mine measure up most completely to an ideal ore environment. Approximately 80 percent of the dominant factors are included in Murphy's review of the geology of this extremely interesting deposit. Closely following with an estimated 70 percentage coverage are the Giant Yellowknife mine (J. D. Bateman), and the Cadillac-Malartic belt (G. W. H. Norman).

A 60 percent dependence upon the factors reviewed in this paper is shown at Bankfield, Tombill, Matachewan Consolidated, Tulsequah Chief, Britannia,

TABLE 2

ELIMINATION CHART COVERING FACTORS ESSENTIAL IN THE ORE ENVIRONMENT



(1) Along access channelways through the medium of pre-ore solutions.
(2) Near intrusive dikes and masses.
(3) Within intrusive masses.

Waite Amulet, Lamaque and Sigma mines. Many more show at least half of the essential conditioning factors, i.e., in so far as the published descriptions would show. Where certain factors appear to be absent, it is commonly found due more to briefness of the geological description than to a factual lack of such features.

In Table 2 an attempt has been made to present the major factors predisposing to the occurrence of ore, in such a way that a determination of their absence may aid in the elimination of certain ground from further condition as a locus for ore. It has been noted that the best place to look for these ore characteristics of the host environment is at the intersection of lineal elements of the regional structure with the tectonic belts. Following on from this, some sort of fracturing (either a fracture pattern or shear faulting) is universally necessary, both to provide host-chambers for the ore, and to permit of the almost essential thermal conditioning that should precede its deposition.

The fracturing must be in a state of tensional dilation, and in general the larger the scale of this opening-up of the fractures or vein fissures, the healthier the outlook. Economically uninteresting veins and stockworks deposits will, however, generally be the result unless there has been an element of *thermal conditioning* introduced into the picture, in order to spread the consolidation phase over as long a period as possible. Pre-heating of the environment may be the result of the fractures lying wholly within an igneous mass, or else sufficiently close to an intrusive body of recent introduction to have been influenced by it, or in yet a third case to have had its temperature raised through the passage of pre-mineralization fluids along the access channelways and through the fracture zones ahead of the ore-bearing fluids proper.

If there is also evidence of fracturing following a partial consolidation of the fracture- or fissure-fillings, and a general indication of a favorable element of timing from the occurrence of the valuable minerals sought, in whatever quantities, at those points otherwise possessing the features outlined above, then it is a relatively safe assumption that conditions of optimum favorability as to all of these factors should be sought within the general area.

Careful formational and structural mapping, coupled with a three-dimensional interpretation and a reconstruction of the geological history of the area, will indicate the points of further attack. Particular attention should be paid to the relative ages of all intrusives, and their place in the time schedule that preceded the appearance of the ore-bearing fluids.

CONCLUSION

The technique of first importance in the search for ore is a study of its environment. The orebodies may be of limited extent, but the different aspects of the mineralization processes frequently show themselves in pronounced fashion over broad areas. Though the ore may be obscured, the rocks that are visible may suggest from their peculiar local features that they represent an ore environment.

The main difficulty has always been that concentration of attention on one dominant factor in the make-up of a particular ore deposit, or type of deposit has led inevitably to the discovery that this is repeated in nature over and over again without any accompanying ore.

Investigation of a number of geological features concurrently will show that it is the presence of a multiplicity of factors that distinguishes the ore environment. It is not enough that some one characteristic be present. More often than not, it is essential that not more than one of the factors discussed be lacking.

Much further study of the pre-determinative factors is indicated, for it is the sad truth that today, after more than fifty years of investigation of the ore environment at an ever-increasing tempo, there is still a great element of chance in the final drill-holes put down hopefully in the quest of an orebody.

The spotting of a drill-hole looks like a relatively easy procedure, and the results are obtained quickly as it goes ahead. Adequate investigation of the chosen environment may take many months, and cost as much as several drill-holes. The conclusion of the campaign of investigation may unfortunately be negative, but in the present state of scientific knowledge of geology, not as emphatically negative as a drill-hole, and therefore not so wholeheartedly trusted.

Much more attention might be paid to the iniation of the engineering and financial elements into the "mysteries" that have been probed in the course of this paper. A break-down of all the factors that can be shown to have influenced the ore probability ratio is the one thing that might be convincingly presented in behalf of the argument for or against any proposal for exploration expenditures.

COLLINGWOOD, ONTARIO, CANADA,
Aug. 9, 1956

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MINERALOGY OF THE LONE EAGLE URANIUM-BEARING MINE IN THE BOULDER BATHOLITH, MONTANA[1]

H. D. WRIGHT AND W. P. SHULHOF

ABSTRACT

The Lone Eagle mine is the only producing uranium deposit among the "base metal" veins in the Boulder batholith, Montana. Steeply dipping fracture fillings in quartz monzonite contain sparsely distributed pitchblende, together with pyrite, sphalerite, galena, and minor chalcopyrite and argentite in a gangue of quartz, calcite and siderite. Deposition of coarsely crystallized quartz and the sulfides was followed by extensive brecciation prior to the introduction of microcrystalline quartz, pitchblende, and minor fine-grained sulfides. The latter assemblage strongly resembles the "siliceous reef" uranium deposits in the batholith. Of the three varieties of pitchblende recognized, only one appears to represent primary introduction of uranium. Detailed data were obtained on the pitchblende varieties and an unusual, fine-grained galena associated with pitchblende.

Study of the wall rock provided detailed information on the nature and composition of the feldspars, the percentage mineral composition and texture of the rock, and its chemical composition. The rock may be classified petrographically as a peraluminous granodiorite (Shand) or an adamellite (Johannsen).

The alteration halo, extending as much as 30 feet from the vein, has a mineral assemblage—sericite, kaolinite, montmorillonite, chlorite, quartz, calcite, siderite, and pyrite—similar to that associated with the "siliceous reefs" and to the Butte alteration described by Sales and Meyer. Of the plutonic minerals, only quartz, apatite, and zircon are found adjacent to the vein. Study of the alteration zoning was inhibited by the lack of adequate samples more than a few feet from the vein.

INTRODUCTION

Since 1949 a number of small uranium showings have been discovered in hydrothermal veins in the Boulder batholith of western Montana. Most of them lie in the northern half of the intrusive, although a few are located in and around Butte. Lead, zinc, gold, and silver are the chief associated metals. Except for minor occurrences of uranium in the copper workings at Butte, few of the deposits contain abundant copper. The deposits have been classed by field geologists of the U. S. Atomic Energy Commission and the U. S. Geological Survey in two general groups: (1) "siliceous reef" deposits containing sparse, finely crystallized sulfides of the base metals and silver together with occasional pitchblende, in a matrix of microcrystalline quartz; and (2) "base metal" veins, characterized by more abundant, coarser base metal and silver sulfides, and pitchblende in a gangue of megacrystalline and micro-

[1] Contribution No. 56-8, College of Mineral Industries, The Pennsylvania State University, University Park, Pennsylvania.

crystalline quartz. The two groups differ chiefly in percentage mineral composition and texture of the ore, rather than in the kinds of minerals represented.

Exploration and development have been actively pursued over the past seven years, chiefly by individual prospectors and small mining companies. Moderately extensive mapping and drilling programs administered by the U. S. Geological Survey and the U. S. Atomic Energy Commission have stimulated the interest and imagination of the residents. Many are convinced that a second Joachimsthal or Great Bear Lake lies at their feet, waiting only to be unearthed. To date, their hopes have been only partially realized, with the shipment of several cars of ore from each of three deposits—the Free Enter-

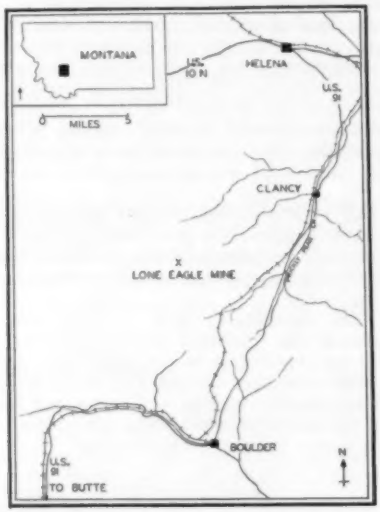

FIG. 1. Index map showing the location of the Lone Eagle Mine.

prise (the discovery claim, near Boulder, now an arthritis mine), the W. Wilson, near Clancy, and the Lone Eagle, about ten miles southwest of Clancy. The first two are "siliceous reefs," while the third is a "base metal" deposit.

Since the summer of 1952, detailed mineralogical investigations of these and other deposits in the batholith have been in progress in the Mineralogy Department of The Pennsylvania State University. The work has been sponsored by Division of Raw Materials and Division of Research of the U. S. Atomic Energy Commission. The general aims of these studies have been to (1) characterize rather fully the host rock, the alteration envelope, the veins, and the blanket of uranium alteration due to weathering, (2) work out the

detailed mineralogy of the uranium, (3) determine the extent of secondary enrichment or depletion of the primary uranium by weathering, and (4) study the relationships of the "siliceous reef" and "base metal" veins to each other and to the non-uraniferous deposits of the batholith.

The present paper is concerned with the Lone Eagle deposit, the only "base metal" uranium-bearing orebody in the batholith now accessible. Other papers now in preparation will deal with the vein mineralogy of the "siliceous reefs," the secondary (weathering) uranium mineralogy, the rock alteration, and some mineralogical relationships concerned with the origin of the deposits which have appeared from the detailed studies. The discussion of the Lone Eagle deposit presented here is largely descriptive, and the study has been of interest chiefly in bringing out certain striking resemblances to the "siliceous reef" bodies. The authors feel that to include the descriptive data accumulated on the latter deposits in a single paper would unduly try the patience of the reader.

The Lone Eagle deposit lies on a tributary of Quartz Creek, about ten mlies southwest of the town of Clancy in Jefferson County (Fig. 1). The Mine was opened before 1900, but most of the development has been done by the present owners on a contract with the Defense Minerals Exploration Administration. Several cars of uranium ore have been shipped since 1952. In 1955 the mine had 290 feet of cross-cuts and three drifts totaling 300 feet, all on the adit level.

THE LONE EAGLE DEPOSIT

Fissures of intermediate to steep dip are filled with megacrystalline and microcrystalline quartz gangue, sulfides, and occasional pitchblende. Sulfides recognizable in hand specimen are pyrite, sphalerite, galena, and a little argentite and chalocopyrite. The microcrystalline quartz ranges from light gray to black, and a small amount is red. The veins, ranging in width up to 24 inches, strike N 33° E to N 47° E, and dip from nearly vertical to 47° SE. Replacement of the walls by vein minerals is minor, and the contacts are sharp. Development of the mine has been complicated by numerous cross and strike faults. The workings are a short distance beneath the water table, and a sooty coating of radioactive material along fractures cutting veins is commonly observed.

The fresh wall rock is a light gray, equigranular, coarsely crystalline biotite-quartz monzonite. Chlorite pseudomorphs after biotite appear at the fringe of the alteration envelope. Toward the vein, development of muscovite and sericite in chloritized biotite is observed, and the feldspars show increasing alteration to montmorillonite, kaolinite, and sericite as the vein is approached. A groundmass of sericite, kaolinite, and fine-grained quartz becomes prominent within about two feet of the vein. A few inches from the vein the rock texture is essentially destroyed; the feldspar pseudomorphs are obliterated, and quartz, sericite, pyrite, and carbonate minerals are the abundant alteration products. No secondary uranium minerals were observed in the mine, although their presence on the dump was reported by Thurlow and Reyner (11).

FIELD STUDY AND SAMPLING

Before collecting samples for mineralogical study, the veins and rock alteration were mapped. Radiometric readings at two-foot intervals along the veins were plotted, and served as an aid in the selection of sample locations.

Early in the field work it became apparent that there was a wide variation in color of the microcrystalline quartz gangue and that a relationship existed between quartz color and uranium content. The varieties of quartz were mapped in an attempt to determine whether their distribution might aid in explaining the spotty localization of uranium. Significant large-scale relationships were not seen from the mapping, and the distribution was of interest chiefly in aiding the selection of sample locations. The uranium and other minor elements in the variously colored varieties of quartz were determined for comparison with the quartz varieties in the siliceous reef deposits. These data will be presented elsewhere.

Seven section samples were taken along a line normal to the vein and extending into wall rock on both sides. Sub-samples were collected at an average interval of 0.2 foot in the vein, 0.3 foot in the wall rock up to two feet from the vein, and 0.6 foot beyond. "Spot" samples were selected for more complete spatial coverage and to represent varieties of vein and wall rock not taken in the section samples.

THE FRESH ROCK

Methods of Study.—The wall rock minerals were identified in thin sections by characteristic optical properties. Orthoclase was stained by Chayes' (5) method. A Rosiwal analysis was made on two stained thin sections, using a total of 2,050 points recorded on 41 traverses of 50 grains each.

To enable detailed study of the minerals, the fresh rock was disaggregated by crushing with a steel mortar and pestle to a size between 150 and 170 mesh. The ferromagnetic minerals were extracted with a hand magnet, and a Frantz isodynamic separator served to remove the biotite, chlorite, and accessory minerals. Bromoform-acetone was used in a separatory funnel to obtain fractions of orthoclase, plagioclase, and quartz, and, after staining, the feldspars were mounted on petrographic slides for microscopic study. Carefully picked fractions of each feldspar were X-rayed with a diffractometer. Albite from Amelia, Virginia was mixed with the orthoclase before x-raying.

Several methods of analysis were employed to determine the composition of the feldspars. Using the method of Bowen and Tuttle (1), the composition of the orthoclase was found by determining the spacing of the $(\bar{2}01)$ planes, controlled by the substitution of Na^+ for K^+. The composition of the plagioclase was determined from the angle (2θ) between the (131) and $(1\bar{3}1)$ reflections (Tuttle, 12).

The beta index of refraction of the plagioclase and the refractive index of the plagioclase glass (using Sosman's method (10)) provided independent data on the plagioclase composition. The glass was obtained by heating for several hours at 1000°C.

Mineralogy.—The Rosiwal analysis yielded the following mineral composition, expressed in volume percentage:

20.7% Quartz	0.2% Siderite
23.4% Orthoclase	0.6% Other non-opaque accessory minerals
35.0% Plagioclase	1.1% Opaque accessory minerals
6.2% Biotite	8.6% Alteration aggregate
4.2% Biotite visibly altered to chlorite	
	100.0%

As indicated by the analysis, the essential minerals are quartz, orthoclase, and plagioclase. Biotite and chlorite are varietal minerals. Light brown biotite shows alteration to chlorite (confirmed by X-ray analysis) along cleavage traces, and chlorite-filled pods represent complete replacement of the biotite. Accessory minerals include hornblende, zircon, tourmaline, sphene, rutile, apatite, siderite, pyrite, and a magnetic opaque mineral, probably magnetite or ilmenite. Aggregates of alteration minerals consisting of chlorite, muscovite or sericite, and fine-grained opaque minerals are present.

The spacing between the $(\bar{2}01)$ peak of the heated orthoclase and the $(10\bar{1}0)$ peak of quartz indicated an orthoclase: albite ratio of 80 : 20. Similarly, the 2θ angle of 0.86 degree between the (131) and $(1\bar{3}1)$ reflections indicates a plagioclase composition of Ab_{62}. The plagioclase feldspar was found from the 2V measurements to be the low temperature (intermediate) variety. The beta index of refraction, 1.548 ± 0.002, reflects a composition between Ab_{64} and Ab_{62} (6), and the refractive index, 1.518, of the plagioclase glass indicates a composition of Ab_{62}.

Chemical Composition.—A chemical analysis (Table 1) of the country rock was computed using the feldspar composition, an analysis of biotite from the Boulder batholith from Weed (13) and stoichiometric mineral compositions listed by Ford (7).

Classification.—The texture of the rock is coarse-grained, equi-dimensional and slightly porphyrytic. The classification is based upon the microscopic description, Rosiwal analysis, composition of the feldspars, and computed chemical composition. The orthoclase to plagioclase ratio is 2 : 3. In terms of pure end-member compositions, orthoclase is more abundant than anorthite, while albite predominates over orthoclase. The quartz to orthoclase ratio is about 1 : 1, and the quartz to plagioclase ratio about 2 : 3. The $Al_2O_3 : Na_2O + K_2O + CaO$ ratio is 2 :3.

In a broad classification based upon essential minerals, the rock may be classified as a biotite-quartz monzonite. In the Shand classification it is a peraluminous granodiorite. The modal analysis places it in the adamellite group of Johannsen.

THE ALTERED ROCK

Along the adit-crosscut, the country rock shows appreciable alteration up to thirty feet from the vein. This was the only exposure—a poor one at that, due to the age of the adit—which permitted collection of samples at distances from the veins greater than five feet. The weathering alteration and the lack of adequate exposures prevented a complete study of the hydrothermal altera-

TABLE 1

STOICHIOMETRIC COMPOSITION, MOL PERCENTAGES, AND CHEMICAL COMPOSITION OF THE QUARTZ MONZONITE

	Vol. %	Sp. Gr.	Wt. % Corr.	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	F	ZrO_2	P_2O_5	S	CO_2	TiO_2	Cl	BaO	MnO
Quartz, Sto.	22.47	2.65	21.958	100.00																	
Mol.				21.96																	
Orthoclase[91]	25.57																				
Ab 20%		2.61	4.823	68.70	19.50					11.80											
				3.38	0.96					0.581											
K 80%		2.57	19.384	64.70	18.40						16.90										
				12.54	3.57						3.28										
Plagioclase[91]	38.14																				
Ab 62%		2.61	22.758	68.70	19.50					11.80											
				15.63	4.44					2.69											
An 38%		2.75	14.698	43.20	36.70				20.10												
				6.35	5.39				2.95												
Biotite[92]	11.45	3.00	12.666	35.79	13.70	5.22	13.72	12.13	0.05	0.15	9.09	4.85	0.76		0.10			3.51	0.20	0.13	0.19
				4.53	1.74	0.66	1.74	1.54	0.01	0.02	1.15	0.61	0.10		0.01			0.44	0.03	0.02	0.02
Siderite	0.31	3.85	0.439				62.10										37.90				
							0.27										0.17				
Pyrite	1.23	5.02	2.275				60.00									53.40					
							1.37									1.22					
Zircon	0.31	4.69	0.535	32.80										67.20							
				0.18										0.36							
Apatite	0.31	0.99 =	0.365						55.50				5.80		42.30						
	99.79		100.010						0.20				0.01		0.15						
Chemical Composition				64.6	16.1	0.7	3.4	1.5	3.2	3.3	4.4	0.6	0.1	0.4	0.2	1.2	0.2	0.4	0.0	0.0	0.0

[91] From X-ray and optical analyses.
[92] Weed (13).
All others from Ford (7).
Sto. = Stoichiometric.
Mol. = Mol. percent.

tion envelope. Detailed studies were limited to the severely altered rock exposed along the drift and within four to five feet of the vein.

Methods of Study.—Thin sections were prepared from chips of every sub-sample in five section samples normal to the vein and extending up to four feet into the wall. Polished sections were prepared from every sub-sample containing appreciable opaque minerals.

The clay minerals were concentrated by decantation. Samples were crushed to minus 10 mesh and quartered with a sample splitter, and quarters 1 and 3 were homogenized and soaked in 0.1 normal sodium carbonate solution for two days to disperse the clay particles. The size range selected included particles theoretically smaller than 0.32 mm. in diameter, obtained by using a settling depth of 10 cm. and a settling time of four minutes at 22° C (Stokes' Law). This fraction was found to represent the best balance between minimum settling time, maximum clay concentration, and minimum concentration of unwanted minerals. Concentrated ammonium hydroxide was added to aid flocculation, and the clays were recovered by centrifuging, decanting the liquid, and oven-drying at 80° C.

Thin sections of each sub-sample were examined, and some of the alteration minerals were identified by characteristic optical properties. The percentage mineral composition was estimated visually and the textural relationships were described.

Diffractometer patterns were made on the clay concentrates from all sub-samples in three sample sections, and alternate sub-samples in the other two. With well-type mounts run by one operator using the same mounting technique and machine settings, reproducibility was judged to be satisfactory for comparison of the reflection intensities from a single mineral in one sample with the same reflections in a different sample, for the purpose of estimating the variation in amount of the mineral across the alteration envelope. Comparison of the reflection intensities for different minerals in the same mount, as a means of estimating percentage mineral composition, was not attempted.

Selected samples of wall rock quartz were X-rayed, and the size distribution of quartz grains was estimated by measuring the longest dimension of 200 grains in each of the size groups described below. Within a size group, grains were selected by predetermined traverses with a point counter.

Alteration Minerals.—The alteration minerals identified in thin sections are chlorite, sericite, muscovite, kaolinite, siderite, calcite, quartz, hematite (?), and pyrite. Montmorillonite, identified in many of the X-ray patterns, was not recognized in the thin sections. The distinction between sericite and muscovite was arbitrary, based upon crystal size: those with a diameter less than about 0.25 mm. were called sericite; larger flakes, muscovite. Chlorite was identified by optical characteristics and confirmed by X-ray analysis.

Occurrence of Alteration Minerals

Clays.—Sericite occurs in flakes and aggregates oriented along cleavage and twin planes in the replaced feldspar. Near the vein, former plagioclase positions may be recognized by "ghost" polysynthetic twinning preserved by

the orientation of sericite shards normal to the length of the twin lamellae. Farther from the vein, sericite was commonly found with kaolinite in dense intergrowths filling fractures in incipiently altered feldspars and fresh quartz.

Kaolinite occurs as dense, platy crystal aggregates; matted, random intergrowths of kaolinite and sericite; and fracture fillings in quartz. Where the minerals are intimately intergrown, sericite and kaolinite cannot be estimated quantitatively as individual minerals.

Quartz.—X-ray analysis proved all of the observed kinds of alteration silica, including some cryptocrystalline material, to be alpha quartz. The thin section studies indicated three more or less distinct crystal size groups. While boundaries between groups are gradational, a smaller percentage of grains falls near the boundary limits than within groups. Point measurements on the largest size group indicated a range from about 0.46 mm. to 6 mm., and an average size of 0.6 mm. A second group ranges from about 0.35 to 0.02 mm., with an average size about the middle of the range, 0.17 mm. A third group by size frequency falls in the range from 0.02 mm. to sub-microscopic. Age differences among the three groups were not apparent, and the significance of this crystal size grouping is not known. As described below in the section on vein mineralogy, the late vein quartz is pronouncedly more fine-grained than the early vein quartz, but a relationship between vein and alteration quartz could not be found.

The alteration quartz exhibits a variety of textures. Coarse crystals (several millimeters long) of plutonic and hydrothermal quartz are disseminated through a matte of clay minerals. Some of the coarse plutonic quartz crystals show overgrowths of apparently hydrothermal origin, while many of the remainder were resorbed and fractured during the alteration. Aggregates of the microcrystalline (introduced) quartz are coated by clay minerals.

In the field, altered rock was classified as "silicified" or "non-silicified" depending upon hardness and apparent degree of cementation. Strongly altered samples of the hard and the friable kinds were found by thin section examination to have about equal amounts of quartz. The difference appears to lie in the crystal size: the hydrothermal quartz in the "silicified" rock is microcrystalline, in contrast to the megacrystalline hydrothermal quartz in the "non-silicified" or friable rock.

Pyrite.—Subhedral to euhedral crystals of pyrite, ranging in size from 0.01 to 0.5 mm., are randomly disseminated through the altered rock, and some crystals, ranging in size from 0.01 to 0.2 mm., are distributed along the cleavage traces of altered biotite. The pyrite tends to be concentrated around the pseudomorphs of muscovite after biotite.

Siderite, Calcite, and Hematite.—Individual rhombehedrons of siderite and calcite are disseminated among aggregates of microcrystalline quartz and clay minerals, and the carbonates line open fractures and vugs in microcrystalline quartz. Hematite forms thin bands lining fractures in microcrystalline quartz; this association is especially characteristic of the more highly radioactive samples of wall rock.

Texture.—The texture of the rock is seen to alter gradually as the vein is approached. All gradations are found between fresh and completely ob-

literated primary textures. Fresh rock texture may be preserved even where the primary minerals are strongly altered, as in cases of clay pseudomorphs after feldspar cemented with microcrystalline quartz. While the obliteration of primary texture can be readily observed in the mine, the disintegrated minerals are more strikingly apparent in thin section. If continuous sections across the entire alteration envelope were available for sampling, it is thought that the extent and nature of weathering alteration could be distinguished from hydrothermal alteration by systematic study of alteration intensity in relation to vein position along a number of section lines. This approach was fairly successful in the nearby W. Wilson deposit, where the veins and alteration envelope were smaller and the exposures better.

Alteration of Primary Minerals

Biotite, plagiclase, orthoclase, quartz, and accessory minerals are present in considerably altered rock at a distance of 30 feet from the vein along the only available exposure, the adit-crosscut. Along the adit, weathering of the altered rock from about five to thirty feet from the vein during the past fifty years has left a rotten mass unsuitable for study. Biotite and the feldspars were not observed microscopically in samples within five feet of the vein, in any of the five section samples studied; here quartz, apatite, and zircon alone represent the primary minerals.

Biotite.—The first indication of hydrothermal alteration of the walls appears in the alteration of biotite to chlorite along the cleavage traces. Chlorite is found about 35 feet from the vein in the adit-crosscut and becomes more abundant veinward for seven feet. At 30 feet from the vein, chlorite and muscovite-sericite pseudomorphs after biotite indicate former biotite positions. Chlorite was not observed within five feet of the vein, and it is probably absent over a much greater distance from the vein which was not available for sampling. Muscovite pseudomorphs after biotite are common here, and their average size diminishes to less than one-half the average size of the original biotite as the vein is approached.

Plagioclase.—The plagioclase in samples from the adit-crosscut 35 feet from the vein is turbid, and fractures are filled with kaolinite. Twenty-eight feet from the vein, the plagioclase is partly replaced by limonite-stained clay minerals. At a distance of five feet from the vein, sericite pseudomorphs after plagioclase have "ghost" polysynthetic twinning, but plagioclase was not identified. Pseudomorphs decrease in abundance from here toward the vein, and their size diminishes to about one-fourth to one-half that of the original plagioclase crystals.

Orthoclase.—Orthoclase is slightly turbid 35 feet from the vein, and at 28 feet it exhibits abundant fractures filled with kaolinite and sericite. Within five feet of the vein, the mineral has been totally replaced by sericite in pseudomorphs which are indistinguishable from the sericite pseudomorphs after plagioclase, except for scattered "ghost" twins in the latter. Due to the lack of exposures beyond five feet from the vein, the relative rate of breakdown of plagioclase and orthoclase could not be studied.

Quartz.—At a distance of 28 feet from the vein, quartz is unaltered, but at

five feet it is considerably embayed and etched. Remnants of apparently plutonic quartz are found next to the vein.

The Clay Minerals

The clay concentrates from elutriation of the altered rock were found from the X-ray spectrometer patterns to contain chlorite, kaolinite, montmorillonite, sericite (hydromuscovite with a basal reflection of about 10.2 Å [3]), and muscovite (basal reflection 10.8 Å, probably containing surplus water between the layers [2]). The kaolinite showed normal optics and the x-ray pattern matched identically a standard pattern of Georgia kaolin. The montmorillonite and chlorite were not studied in detail. Peaks from minor quartz, orthoclase, and plagioclase appeared in most of the patterns.

In order to compare the alteration pattern in this "base metal" deposit with the alteration surrounding the "siliceous reefs," which had been worked out in some detail, an attempt was made to determine the distribution of sericite, kaolinite, and montmorillinite, taken separately, in successive subsamples at increasing distances from the vein. In the "siliceous reef" deposits, plots of concentration against distance from the vein showed peaks for sericite, kaolinite, and montmorillonite at successively greater distances from the vein, as was demonstrated in the Butte district by Sales and Meyer (9). At the W. Wilson deposit, for example, five sample sections from different levels of the mine all showed this pattern. X-ray spectrometer patterns were made on six to ten sub-samples in each section, and peak heights for each of the three major clays were compared from one sub-sample to the next.

In the W. Wilson deposit the altered rock generally occupied only a few feet between vein and fresh rock, and complete, continuous sections were obtainable at many places in the drifts. In the Lone Eagle deposit, the lack of recent cross-cuts prevented collection of fresh samples at distances greater than four to five feet from the vein. This left most of the alteration envelope unsampled except for the rather rotten rock in the old adit.

The distribution of sericite and kaolinite across about four feet of rock in the first section analyzed conformed to the pattern in the "reefs," with the peak for kaolinite farther from the vein than that for sericite. A trace of montmorillonite appears in two samples in the last foot of this section. The other four sections, however, failed to confirm this pattern. No regular trend —or radical fluctuation—for either sericite or kaolinite was found. Montmorillonite appeared spasmodically in the outer parts of the sections. It seems probable that the data from about one-fifth of the width of the altered rock is insufficient to demonstrate a regular pattern of distribution of the clays. If a greater width of the envelope could be sampled, a pattern similar to that in the reefs and at Butte might be found, as suggested by the similar alteration mineral assemblage and the distribution pattern in one section.

Discussion of the Rock Alteration

Although the study of the altered rock did not fully characterize the alteration envelope and establish mineral abundance trends, it yielded sufficient information to establish the general nature of the alteration. Microcrystalline

quartz is the most abundant mineral immediately adjacent to veins, and sericite is the predominant clay mineral. Sericite is observed in all thin sections and X-ray patterns of material close to the vein, while the other clay minerals are irregularly found in both thin sections and X-ray patterns. Kaolinite is next to sericite in abundance. Although kaolinite peaks are commonly absent in the X-ray patterns, the mineral is usually recognized in thin sections in amounts of several percent or more. Microscopic study revealed that the quartz content of the altered rock averages about 25 percent, and is considerably higher close to veinlets transecting the rock. The relatively uniform heights of the quartz peaks indicate a rather restricted range in quartz abundance. This small variation in quartz content supports the interpretation from microscopic evidence that the cohesion of the altered rock is a function of the quartz distribution and crystal size rather than amount.

X-ray patterns of strongly altered rock within five feet of the vein show the presence of a little feldspar, but only clay pseudomorphs after feldspar were observed in the thin sections. Fine, isolated feldspar remnants may give rise to the X-ray pattern. Quartz, apatite, and zircon are the remnant plutonic minerals next to the vein. Apatite and zircon remained essentially unchanged during alteration.

The carbonate minerals consistently present in the amount of five percent, and the five percent of pyrite may have been derived from the fresh rock by hydrothermal processes. If all of the 2.4 percent of iron from biotite of the fresh rock were released during alteration, it would be sufficient to form about seven percent pyrite, or about eight percent siderite. Similarly, if the three percent of calcium from the plagioclase of the fresh rock were released during alteration, it would be sufficient to form about eight percent calcite. By allowing for the known extensive solid solution between siderite and calcite and assuming that the bulk of the iron and calcium released did not escape into the vein, the amount of pyrite and siderite is within the limits of iron and calcium in the fresh rock available to form them. It seems probable that the sulfur and carbon dioxide were added by the hydrothermal solutions.

THE VEINS

The emphasis in the vein mineralogy study was placed on the nature of the pitchblende and its relationships to the other vein minerals. The work involved mainly identification and characterization of the ore and gangue minerals and interpretation of their textural relations, together with detailed mineralogical study of the pitchblende and a peculiar fine-grained variety of galena.

Study of polished sections and matching thin sections permitted identification of most of the vein minerals and interpretation of age relationships from their textural relations. The microscopic identifications were supplemented by microchemical tests, X-ray analysis, and spectrographic analysis using material gouged from polished sections under the ore microscope. The X-ray photographs were made in a Straumanis camera with copper radiation. Uncontaminated samples of ore minerals other than pyrite, sphalerite, and galena were difficult to obtain because of their small grain size.

The Ore Minerals

Pyrite—Pyrite occurs in euhedral to anhedral crystals and aggregates, and in veinlets, stringers, and overgrowths on euhedral pyrite. Individual crystals range from five mm in length to submicroscopic size.

Chalcopyrite.—Chalcopyrite occurs sparingly in irregular masses up to 0.25 mm in diameter, and as formless inclusions in sphalerite, commonly aligned along cleavage traces.

Sphalerite.—Sphalerite is found in anhedral masses from a few microns to about 5 mm. in diameter. It is abundant in most of the sections, and is closely associated with galena and chalcopyrite.

Galena.—Galena occurs in two distinct varieties. Common galena, showing the characteristic light gray color, high reflectivity, and cleavage pits is called galena A. Galena A forms subhedral to anhedral grains ranging in size from several microns to about 2 mm in diameter, and is commonly associated with sphalerite.

The second variety, galena B, is soft, appears to be somewhat malleable, and has a light tan-gray color and a low but variable reflectivity. It occurs in formless bodies from a few microns to 0.5 mm across, filling vugs; or in intergrowths with other vein minerals, especially pitchblende. Galena B was identified by microchemical tests, spectrographic analysis, and X-ray. A considerable amount of work was done on galena B which will be published separately after a lead isotope analysis has been obtained for comparison with galena A.

Argentite.—Argentite was inconclusively identified in the polished sections, and the identification was confirmed by X-ray examination. It forms anhedral bodies along the walls of veins adjoining soft altered rock, and generally is isolated from the other ore minerals.

Unidentified Minerals.—Several other minerals were observed in intricate intergrowth with pitchblende, galena B, and argentite. Their extremely small size made positive identification impossible, but their white color and the association suggest silver sulfosalts, possibly associated with native silver, or perhaps cobalt-nickel sulfides, sulfarsenides, or sulfantimonides. The presence of some silver, cobalt, and nickel in the vein material was found in the spectrographic analyses.

Gangue Minerals.—The gangue minerals are quartz, siderite, and calcite. The quartz shows a wide range in crystal size from a length of several millimeters to sub-microscopic size. Much of the microcrystalline quartz forms homogenous aggregates of anhedral crystals with a rather narrow size range in any one place. Comb structure, exhibited by some microcrystalline quartz, is more common in the coarse quartz.

Varieties of Pitchblende

Three textural varieties of pitchblende were observed. Pitchblende A and B were observed both in hand specimens and polished sections; pitchblende C was identified only in hand specimens. Pitchblende A is black, rela-

tively hard, brittle, has a pitchy luster, and forms grains up to 2.0 mm in diameter. In polished section it is medium gray, about as hard as a steel needle, and forms irregular bodies filling fractures and vugs. In hand specimen, pitchblende B is gray-black, compact, and has a dull luster. In polished section it appears in irregular patches of a dull gray material somewhat softer than pitchblende A (its hardness varies considerably but is always less than the steel needle). Pitchblende B fills fractures and vugs and is intergrown with microcrystalline quartz. Pitchblende A and B are disseminated together with fragments of sulfides through the gangue and breccia cement. Pitchblende C is black and sooty, very dull lustered, and coats pitchblende B and the walls of late fractures cutting the vein. The surface of pitchblende in polished sections appears mottled, probably because of the close association and intergrowth of pitchblende A and B, and galena B. Some botryoidal forms of pitchblende were observed but these were not especially characteristic of the material as a whole.

The different appearance, physical properties, and occurrence of the several pitchblende varieties suggest different degrees of oxidation. From the work of Brooker and Nuffield (4) on the oxidation state of pitchblende, it was thought that the hard, lustrous pitchblende A might be expected to have the lowest U^{6}/U ratio, whereas the sooty pitchblende C should, perhaps, be the most highly oxidized, with the highest U^{6}/U ratio. The oxidation state of pitchblende B was expected to lie between these values. Specimens of each variety of pitchblende were gouged from polished sections and cleaned, and spindles prepared for X-ray. The best exposure time with copper K-alpha radiation to achieve maximum contrast of reflections above background was found to be about 24 hours. The unit cell dimension was determined from one Debye pattern on each of the three pitchblende varieties.

As was expected, the diffuseness of the reflections increased and the number of identifiable high angle reflections decreased progressively from pitchblende A to pitchblende C. However, the expected progressive decrease in lattice constant from pitchblende A to pitchblende C was not found.

Pitchblende C, as expected, has a smaller cell edge (5.41 Å) than either pitchblende A (5.42 Å) or pitchblende B (5.44 Å). The larger lattice constant of pitchblende B than of A, however, does not fit the picture, and the explanation is not known. It is possible that the dull luster of pitchblende B may represent only a surface oxidation effect, while the bulk is unoxidized. Some evidence for this has been seen in the polished sections in the brighter luster of the pitchblende cores than the mantles. The use of lattice constant variation for a satisfactory estimate of the degree of oxidation would require correlation with careful density measurements to detect excess oxygen, and probably good chemical determinations to determine the extent of possible lattice substitutions—a difficult chore for this fine-grained, impure mineral. In the absence of specific gravity and adequate compositional data, and especially with only the single determination made on each of the three varieties, it is thought that little significance can be attached to the observed unit cell variation.

Distribution of Radioactivity in the Ore

The spotty distribution of radioactivity in the veins, and from one vein to another, is striking. The radioactive and non-radioactive veins are similar in their mineralogy and texture, and differ in no apparent way other than presence of pitchblende. Both kinds contain the sulfide minerals described above, together with microcrystalline quartz, some megacrystalline quartz, fragments of altered wall rock, and shards of sericite.

A fairly consistent association of strong radioactivity with either red or dark gray microcrystalline quartz has been used as a prospecting guide. Microscopically, the red quartz is seen to consist of relatively coarse microcrystalline quartz intergrown with shards and aggregates of sericite stained orange-yellow (probably by limonite).

Autoradiographs made from polished sections were compared stereoscopically with enlarged photographs of the sections to locate the sources of activity. The red quartz was found to be non-radioactive, but radioactive material closely associated with it is concentrated around breccia fragments in a groundmass of very fine dark gray microcrystalline quartz. Fractures transecting both red and gray microcrystalline quartz as well as the breccia and the sulfide minerals are lined by pitchblende, and filled by comb quartz or more pitchblende. Pitchblende A and galena B are commonly observed as vug fillings in the microcrystalline quartz. This association tends to support evidence from cross-cutting relationships indicating that the pitchblende A-galena B-microcrystalline quartz deposition followed the period of major sulfide development.

Paragenesis of Vein Minerals

From the textural relationships observed, chiefly cross-cutting and open space filling, the depositional history of the Lone Eagle veins has been interpreted to be about as follows:

1. Megacrystalline quartz and well crystallized pyrite, the earliest minerals, were formed at frequent intervals if not continuously through the vein mineralization.

2. Sphalerite, chalcopyrite and galena A were nearly contemporaneous; most of the sphalerite and chalcopyrite preceded the galena. "Stringy" and anhedral pyrite formed. The argentite is tentatively assigned to this stage, although its relations are inconclusive.

3. Brecciation of wall rock, vein quartz, and sulfide minerals followed the main sulfide stage (2.). Breccia fragments were cemented by microcrystalline quartz, and coarser quartz filled open spaces in the veins.

4. Pitchblende A and B were deposited together with Galena B, microcrystalline quartz, minor sphalerite, and pyrite.

5. Minor amounts of sphalerite, galena, and pitchblende were deposited with extremely fine microcrystalline quartz during and after a period of brecciation at the close of (4.).

SUMMARY AND CONCLUSIONS

The Lone Eagle mine has features characteristic of both the "older" (post quartz monzonite, pre dacite-rhyolite) and "younger" (post dacite-rhyolite) groups in Knopf's (8) classification of vein deposits in the Boulder batholith. The abundance of base metal sulfides (pyrite, sphalerite, galena, chalcopyrite) and scarcity of precious metals, together with the early megacrystalline quartz gangue, resemble features of deposits belonging to the older group. The abundant microcrystalline quartz which formed late in the paragenetic sequence, and the relative scarcity of base metal sulfides associated with it, are suggestive of Knopf's "younger" vein group. It is interesting that the main megacrystalline quartz—base metal sulfide deposition was followed by strong brecciation prior to the microcrystalline quartz—minor base metal sulfides—uranium mineralization. Stages 3 to 5 of the paragenetic sequence show a striking similarity to the "siliceous reef" deposits.

The country rock, generally referred to as a quartz monzonite, may be classified petrographically as a peraluminous granodiorite (Shand) or an adamellite (Johannsen). The rock was strongly altered preceding and during vein deposition. In the opening stage of alteration biotite was chloritized and scattered patches of clays formed in the feldspars. In the next stage the chlorite-biotite grains gave way to sericite which preserved the original biotite outlines, and the feldspars were replaced by pseudomorphous sericite-kaolinite mattes. In the final, most intense stage, the feldspar and biotite pseudomorphs underwent further disintegration with the introduction of abundant cementing quartz, siderite, and calcite, which together with the sericite and kaolinite, formed a fine-grained groundmass about the remnant apatite, zircon, and plutonic quartz.

Much of the alteration belonging to the intermediate and early severe stages is obscure due to lack of adequate exposure. The alteration pattern, as far as can be determined, is quite similar to that in the "siliceous reefs," which was studied more fully, and to the pattern in the Butte district described by Sales and Meyer. The chief difference is in the minor amount of montmorillonite found in the limited exposures of the Lone Eagle alteration envelope. This mineral generally is farthest from the vein in the sequence sericite—kaolinite—montmorillonite, and considering the 20 to 30 foot alteration width, it would not be expected in large amounts in the severely altered rock within five feet of the vein, available for study.

Three varieties of pitchblende, called A, B, and C, were recognized. Of these only pitchblende A is believed to represent original hydrothermal introduction of uranium. Pitchblende B appears to grade into A and is believed to represent original (A) nodules either oxidized around the borders or in some cases, dissolved and redeposited by later hydrothermal solutions. Pitchblende C, a sooty form, is found on late, weathered fractures cutting the vein and is thought to represent leaching, movement, and redeposition by groundwater.

An attempt to correlate the degree of oxidation of the pitchblende, as indicated by diffuseness and spacing of the X-ray reflections, with the occurrence

of pitchblende A, B, and C was only partly successful. Good correlation with progressive diffuseness of the X-ray reflections was obtained, but the lattice constant from single patterns of each variety varied irregularly.

Characteristic high or low temperature ore minerals indicative of the physical environment at the time of deposition are lacking. The mineral assemblage, together with the evidence of brecciation and abundant open space filling compared with the relative unimportance of wall replacement by the ores, vaguely suggests deposition under moderate temperature conditions and low to moderate pressures—the mesothermal class of Lindgren.

From the similarity in vein mineralogy and paragenesis and the wall rock alteration, it is thought that uranium was introduced in the reopened Lone Eagle deposit contemporaneously with the deposition in siliceous reefs. Further evidence supporting this conclusion, from uranium-lead age determinations, lead isotope analyses on galenas, and color, texture, and trace element studies on microcrystalline quartz in the "base metal" and "siliceous reef" deposits, will be presented elsewhere.

ACKNOWLEDGMENTS

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INTERGROWTHS OF PENTLANDITE AND PYRRHOTITE

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ABSTRACT

Heat treatment of $(Fe,Ni)_{1-x}S$ solid solutions, equivalent to some nickeliferous pyrrhotites is shown as giving rise to oriented blebs, stringers and rims *as well as apparently cross-cutting "veins"* of pentlandite in pyrrhotite. As the process must involve diffusion of iron, nickel and sulfur these intergrowths and segregations of pentlandite are attributed to exsolution following particularly loss or readjustment of sulfur between pyrrhotite and pentlandite, as indicated in the latter case by Kullerud. Fracturing and late introduction of chalcopyrite are suggested as factors aiding such ex-solution in natural ores. Some of the products illustrated resemble natural occurrences but others do not. "Veins" of pentlandite are thus not necessarily due to crystallization from a liquid of this composition.

INTRODUCTION

Some years ago following a study of intergrowths of niccolite and maucherite an explanation was offered by the senior author (with D. F. Hewitt, 3) for some natural intergrowths of pentlandite and pyrrhotite, based on heat treatment of artificial nickeliferous pyrrhotites. Detailed results were not published at the time and an opportunity to present these has not arisen until recently. As similar features displayed in the samples so treated have not been described by others in the interval, it appears timely to note the results of this work with actual illustrations.

In 1947 Lundqvist demonstrated that the B-8 type of pyrrhotite ($Fe_{1-x}S$) with sulfur in excess of 51.0–51.4 atomic percent forms a continuous series of solid solutions with the isomorphous high-temperature modification of NiS above a temperature of 396° C. Colgrove (1) had earlier (unpublished doctorate thesis, Univ. Wisconsin) determined the existence of a solid solution series with the B-8 structure between FeS-$FeS_{1.18}$ and what he termed γ-solid solution of $NiS_{0.82}$-$NiS_{1.08}$. Kullerud (5) has more recently confirmed this series of solid solutions which form above 396° C and extend continuously from FeS-Fe_7S_8 to NiS-$Ni_{12}S_{13}$ "solubilities on both sides increasing markedly with increasing temperatures." [1] In the range from 20 mol percent NiS to less than 70 mol percent, $(Fe, Ni)_{1-x}S$ mix crystals are more restricted in variation of metal to sulfur and follow more closely the Fe_7S_8-$Ni_{12}S_{33}$ join, whereas along the FeS-NiS join a two phase field of pentlandite $(Fe, Ni)_9S_8$, and $(Fe, Ni)_{1-x}S$ mix crystals occurs. Thus, a vertical section along $(Fe, Ni)_{15}S_{11}$ to $(Fe, Ni)_9S_8$ (pentlandite), with Fe : Ni = 1, shows pyrrhotite mix crystals, $(Fe, Ni)_{1-x}S$, forming from liquid with a range of metal to sulfur of 7.5/8 to about 7.92/8, beyond which pentlandite forms in eutectic relation

[1] Personal communication.

with the mix crystals. The eutectic temperature is 845° ± 5° C. On cooling the pyrrhotite mix crystals with a maximum metal to sulfur of about 7.85/8 at 845° C, require more sulfur, metal to sulfur at 500° C being 7.6/8—"and this demand is met by exsolution of (the lower sulfur) pentlandite." Kullerud's results thus aid in explaining intergrowths of pyrrhotite and pentlandite illustrated in this paper.

PREPARATION OF $(Fe, Ni)_{1-x}S$ SOLID SOLUTIONS

To prepare nickeliferous solid solutions powdered iron, nickel and sulfur were carefully mixed in the desired proportions and charged in 2½ gram lots in vitrosil tubes which were evacuated and then sealed. All iron was freshly reduced in hydrogen before using. Charges were first heated to 500–600° C for 24 hours and the temperature was then raised to 1,300° C for 1 hour to allow complete fusion. Products from the first heat treatment proved too porous and fine grained for microscopic examination, but after fusion, followed by slow cooling (48 hrs.), the products were coarser grained though still rather friable. One half of each product was then used for X-ray analysis by the powder method and the other for a polished section. Other methods of preparation are detailed by Colgrove (1).

Metal to sulfur ratio in one set of charges was kept at 1 : 1.2 (6.66 : 8), but the actual ratio in the products formed was not determined and in all probability was slightly higher. In this set Fe : Ni was varied as follows: 5/95, 10/90, 20/80, 30/70, 55/45 and 70/30. Except for the last mixture perfectly homogeneous products were obtained yielding a B-8 pyrrhotite X-ray pattern, the lines spreading with increasing nickel content. Some thirty charges were run but many were discarded due to cracking of tubes on cooling. Reactions between constituents began at about 300° C. In all cases where cracks developed on cooling with attendant loss of sulfur it was noted that a second phase (pentlandite) appeared with the solid solution, developing either around grain boundaries or as oriented blebs or veinlets within the pyrrhotite.

In two other charges metal to sulfur was kept at 1 : 1 and 9 : 8, respectively. In the first (No. 10) Ni : Fe was 10/90 and in the second (No. 11), 68/32. Though a hair-like crack developed in the tube of No. 10 on cooling it did not appear sufficient to allow loss of sulfur but some such loss may have occurred. The product obtained showed two phases, a pyrrhotite with pentlandite in oriented sinuous strings which broadened to ragged patches. Small ragged vein-like masses were also present at grain boundaries, both textures suggestive of ex-solution but not of a eutectic relation. No. 11 fusion, designed to give a high-nickel pentlandite consisted chiefly of isotropic pentlandite, with a very minor slightly anisotropic phase, likely a nickel sulfide. This confirmed the direct crystallization of a high nickel pentlandite from a low sulfur melt with an Ni/Fe ratio close to 68/32.

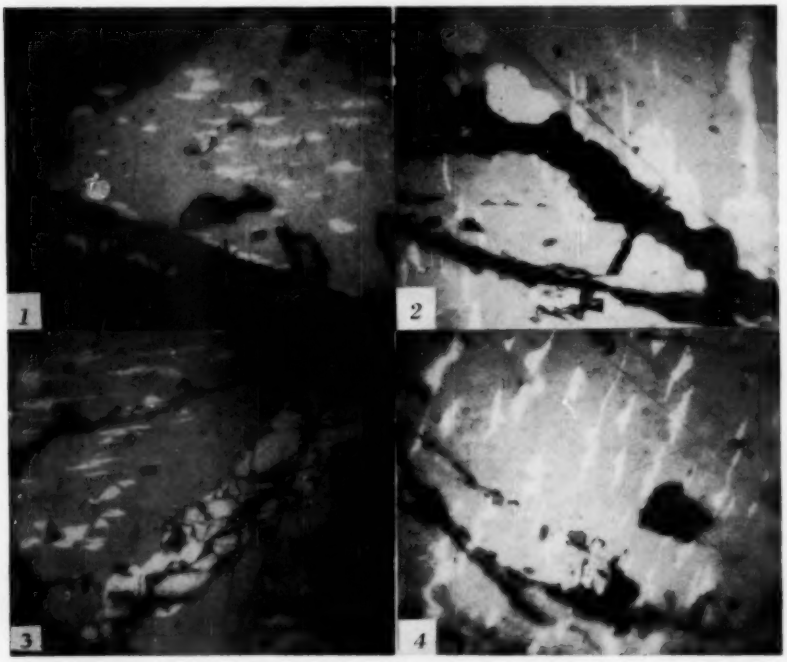
HEAT TREATMENT OF $(Fe, Ni)_{1-x}S$ SOLID SOLUTIONS

Heat treatment of portions of prepared $(Fe, Ni)_{1-x}S$ solid solutions was carried out in a tube furnace in a current of nitrogen. As heating at 370° C

for 12 hours showed no change in a product (Fe, Ni)$S_{1.20}$ (Ni : Fe = 30/70), this and other specimens were subsequently heated to 800° C for 72 hours followed by a cooling period of 48 hours. Sulfur was thus allowed to escape.

Results of Heat Treatment.—Examination of polished sections of heat-treated nickeliferous solid solutions showed the following results:

1. (Fe, Ni)$S_{1.2}$ (Ni:Fe = 5:95). Two separate samples showed no change; specimens still homogeneous pyrrhotite.



FIGS. 1–4. Products of heat treated solid solution $(Fe,Ni)_{1-x}S$ with Ni:Fe = 10:90. Gray-pyrrhotite, white-pentlandite, × 680.

FIG. 1. Oriented blebs and lenses of "pentlandite" in "pyrrhotite" and rim of "pentlandite," lower border.

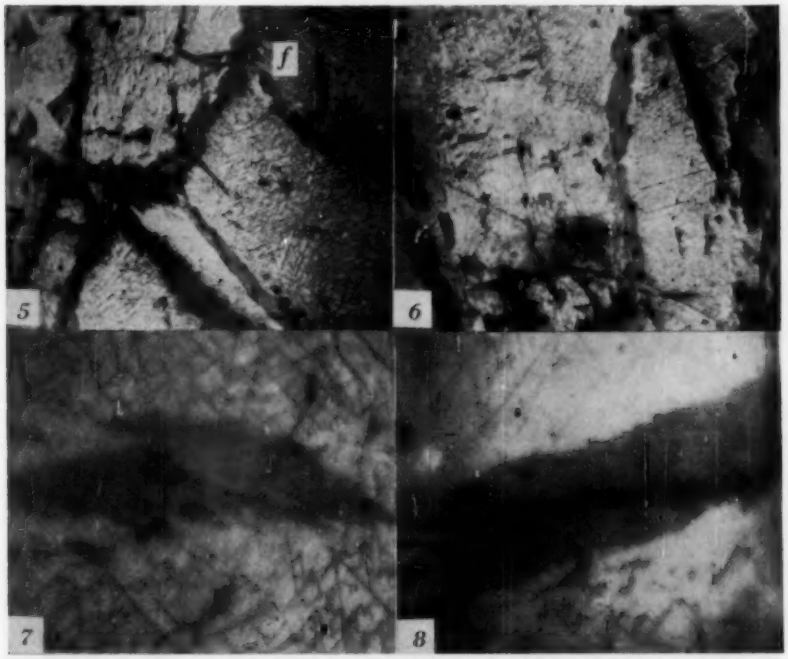
FIG. 2. Flame-like segregations of "pentlandite" in "pyrrhotite."

FIG. 3. "Vein" of granular "pentlandite" at angle to oriented blebs. Area of "pyrrhotite" adjacent to "vein" is relatively free of "pentlandite."

FIG. 4. Oriented strings and lenses of "pentlandite" in "pyrrhotite," similar to some natural intergrowths.

2. (Fe, Ni)$S_{1.2}$ (Ni; Fe = 10 : 90). Pentlandite formed in oriented blebs, lenses flames, and in one place as a distinct vein, as illustrated in Figures 1–4. Figure 1 shows oriented blebs of pentlandite, white, as well as a partial rim at the base of a grain of pyrrhotite (gray). Figure 2 shows

flame-like segregations of pentlandite, and Figure 3 shows a diagonal vein of granular pentlandite cutting pyrrhotite at about 45° to the basal parting which is indicated by the finer blades and lenses of oriented pentlandite. It is interesting to note that adjacent to the vein of pentlandite the pyrrhotite is rela-



FIGS. 5–8. Products of heat treated solid solution $(Fe,Ni)_{1-x}S$ with Ni:Fe = 55:45.

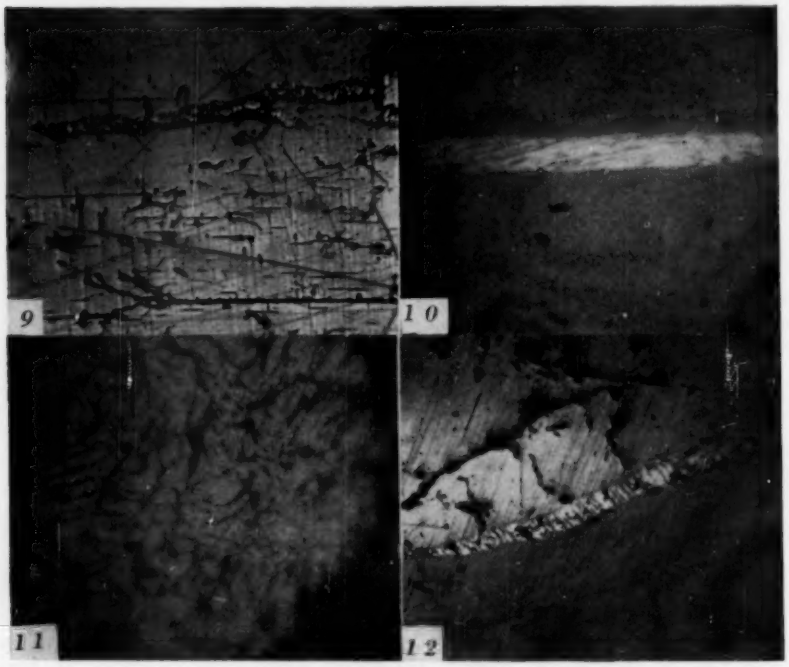
FIGS. 5, 6. Widmanstätten texture of fine blades of "pentlandite" (medium gray) in "pyrrhotite" (light gray to white). Note also patchy distribution of gray blebs of "pentlandite" "flames" (f) Figure 5, and "veins" Figures 5–6, between different grains of host. × 70.

FIG. 7. A bleb of "pentlandite" in "pyrrhotite" of Figure 5, in greater detail. × 680.

FIG. 8. Portion of a "vein" of "pentlandite" from Figure 5, × 680. Note en echelon character of "pentlandite." Compare with natural pentlandite. Figure 10.

tively free of the finer "ex-solution" blades. In Figure 4, oriented veinlets with irregular swellings are present and are almost identical with some natural ores. It appears then that the development of the pentlandite in both oriented masses and in the cross-cutting vein has been due to diffusion or segregation from the original solid solution, initiated by loss of sulfur. The actual Ni/Fe

ratio of this segregated pentlandite was not determinable but undoubtedly is within the range of artificial pentlandites prepared by Kullerud and Lundqvist, that is well above the composition of the original solid solution used. Hence nickel ions must have diffused toward the segregations and iron into the pyrrhotite. Loss of sulfur to raise the metal/sulfur ratio to that of pentlandite may well be expected to have occurred most readily along basal partings and along the fracture into which "vein" pentlandite diffused. This would account for the location of both types of pentlandite in addition to other crystal-



FIGS. 9–12. Natural intergrowths of pentlandite in pyrrhotite, Sudbury area.

FIG. 9. Oriented vein-like pentlandite and short (black) blades of pentlandite in pyrrhotite in section perpendicular to plane of parting. × 25.

FIG. 10. Oriented vein-like pentlandite (white) in pyrrhotite (gray), same section as Figure 9, × 720. Compare en echelon structure with artificial product, Figure 8.

FIG. 11. Cross section of Figure 10, cut parallel to plane of parting. Pentlandite—white, pyrrhotite—gray. × 720. Note particularly the contrasting distribution of pentlandite compared with Figure 10, due to difference in orientation of section. The texture might be described in part as "rosette."

FIG. 12. Pentlandite (white) occurring in chalcopyrite (dark gray bottom) as a fringe along contact between chalcopyrite and pyrrhotite (lighter gray, top). × 60. Elsewhere chalcopyrite veins or replaces pyrrhotite.

lographic controls. That some sulfur may also have diffused into the pyrrhotite phase is suggested by Kullerud's work, in that pyrrhotite requires more sulfur on cooling. Both the vein and oriented intergrowths of pentlandite in pyrrhotite are thus interpreted as a special case of unmixing of a solid solution.

3. $(Fe, Ni)_{1-x}S_{1.20}$ (Ni : Fe =20 : 80). This product after similar heat treatment showed only a few oriented flames of pentlandite in pyrrhotite but a much larger proportion of pentlandite in isolated granular aggregates. Due to disintegration of the specimen on polishing no suitable reproduction of the resulting texture was obtained. It is interpreted however as showing nearly complete segregation or unmixing of pentlandite.

4, 5. $(Fe, Ni)_{1-x}S$ (Ni : Fe = 30 : 70 and Ni : Fe = 55.45). After heat treatment these two specimens both gave peculiar Widmanstätten intergrowths, not duplicated in natural ores as far as the writer is aware. In addition irregular lenses, flames, and "veins" of pentlandite developed, some along grain boundaries of pyrrhotite, thus resembling cell or net textures. Products from the higher nickel solid solution are illustrated in Figures 5–8.

The Widmanstätten texture is shown in Figures 5 and 6. Pentlandite is darker gray and has developed in narrow blades along three intersecting directions for which no explanation can be offered at this time, though the texture suggests segregation along pyramidal directions in the pyrrhotite.

It should be noted that the solid solution (No. 5) from which these products were obtained contained originally sufficient nickel, so that on reduction of the sulfur to metal ratio to 8/9 it should have been converted completely to pentlandite. The ability of pyrrhotite to take up sulfur and retain it on cooling, as indicated by Kullerud, may explain the incomplete conversion of the pyrrhotite solid solution. The occurrence also of flames of pentlandite along cracks, oriented blebs and "veins" of pentlandite is similar though somewhat less prominent than in specimens illustrated in Figures 1–4.

Greater magnification of a bleb of segregated pentlandite and of a "vein" are shown, respectively, in Figures 7 and 8. Attention is called in both to the *en echelon* arrangement of the (gray) pentlandite. This is similar to the arrangement of a natural vein-like mass of pentlandite in a Sudbury specimen of pyrrhotite, Figures 9–10.

DISCUSSION AND CONCLUSIONS

Heat treatment at 800° C of synthetic $(Fe, Ni)_{1-x}S_{1.2}\pm$ homogeneous solid solutions with varying Ni : Fe ratios, accompanied by loss of sulfur gives rise to oriented blebs, lenses, flames, granular aggregates and even "veins" of pentlandite in pyrrhotite which resemble in many ways various natural occurrences of these minerals. One case is noted of segregation of pentlandite along three (pyramidal?) directions in pyrrhotite rather than along the more common basal partings. High magnification of both blebs and vein-like pentlandite shows it to have an en echelon arrangement at a low angle to basal parting, as in natural specimens.

All of these intergrowths were formed under sub-solidus conditions and must have required diffusion of the constituent atoms. They appear to be

due essentially to loss of sulfur, resulting in part in the formation of the lower sulfur compound, pentlandite, though it is possible adjacent pyrrhotite also acquired some additional sulfur from the pentlandite phase on cooling (Kullerud). The intergrowths are thus logically interpreted as due to ex-solution, and particularly to the peculiar effect of change in sulfur concentrations in the phases present.

Natural nickeliferous sulfide ores consist dominantly of pyrrhotite with lesser quantities of pentlandite and chalcopyrite. Average pentlandite in some ores is about 10 percent,[2] and average Ni/Fe is probably less than 10/90. Textural relations of pyrrhotite and pentlandite are intimate and dominantly of an ex-solution type. Rarely, as in the Lynn Lake ores of Manitoba, does pentlandite cross-cut pyrrhotite in vein form, suggestive of formation from a pentlandite liquid. Chalcopyrite is almost invariably later than both other sulphides and replaces and veins them. It is thus suggested that in ores where pyrrhotite and pentlandite appear pene-contemporaneous, deposition of an original $(Fe, Ni)_{1-x}S$ solid solution first took place, subsequent unmixing of pentlandite occurring on cooling, and particularly wherever fracturing allowed a decrease or rearrangement of the sulfur content. The later invasion of copper rich fluids to form a late chalcopyrite may also have aided in the sulfur rearrangement and hence the ex-solution of pentlandite. This possibility is illustrated by the occurrence of flames of pentlandite along the contact of pyrrhotite and chalcopyrite on Figure 12. As chalcopyrite has virtually no solubility for nickel, there is no tendency for it to be incorporated in it.

According to this interpretation such ores originally formed from magmatic sulfide melts, and crystallized as nickeliferous solid solutions. The relatively high iron and low nickel content of such ores clearly places such melts initially in the "pyrrhotite" solid solution field of Kullerud rather than in the field from which $(Fe, Ni)_{1-x}S$ mix crystals and pentlandite would crystallize in eutectic relation.

Later on cooling, with loss and possibly readjustment of sulfur, separation of pentlandite occurred in one or more generations or over a period of time, aided in part by heat effects of later copper rich fluids. A few ores do suggest the presence of pentlandite-rich liquids following deposition of pyrrhotite, but to the writer's knowledge none show typical eutectic textures of a type which might be expected from the eutectic relations indicated by Kullerud. While it was previously suggested (4, p. 383) that such liquids (low in nickel and/or sulfur) might crystallize according to a peritectic diagram and thus yield low nickel pyrrhotite and a pentlandite rich liquid, no confirmation of this has been obtained by recent experiments. If such pentlandite-rich liquids do not form in nature it is suggested that the apparently cross-cutting veins of natural pentlandite in pyrrhotite may alternatively be explained by the peculiar type of "ex-solution" illustrated herein.

Further study of the stability (under desulfurizing processes) of low-nickel $(Fe, Ni)_{1-x}S$ mix-crystals with $Ni : Fe = 5 : 95$ or less, appears re-

[2] G. L. Colgrove, Personal communication.

quired as only richer nickel solid solutions in our experiments gave rise to pentlandite intergrowths and "veins."

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DAVIDITES FROM THE MT. ISA–CLONCURRY DISTRICT, QUEENSLAND

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ABSTRACT

The mineralogy and composition of a number of varieties of davidite from the newly discovered uranium field in the Mt. Isa-Cloncurry District of Queensland are described. The davidites, which occur disseminated in Archaean schists and granulites, exhibit a number of interesting microtextures and show a wide variation in U_3O_8 content. In one instance the uranium content appears to be shared between davidite and ilmenite with which the former is intergrown. Field evidence together with an unusually diverse variety of trace elements indicate a geosynclinal origin for the davidite and associated minerals.

INTRODUCTION

THE uranium minerals of the Mt. Isa-Cloncurry District of Western Queensland occur in a variety of rock types in both the Archaean and the Older Proterozoic. Mineralization has been ascribed variously to processes of regional metamorphism, contact metamorphism, and contact metasomatism and to replacement within orthomagmatic intrusions of alaskite (4).

The principal primary uranium minerals found to date are uraniferous allanite, brannerite and davidite. It is with the latter of these minerals that the present paper is concerned.

The main occurrences of davidite are in the schists and granulites of the Argylla Series, where the mineral is fairly widespread in small amounts. It has been found at various localities from Kajabbi, some fifty miles north of Cloncurry, to a point a few miles north east of Dajarra, i.e., a north-south trending belt nearly 200 miles long and 60 miles wide (Fig. 1).

MINERALOGY

Three distinct types or varieties of davidite can be recognized in the field; they have the following features:

Type 1.—Jet black in color and homogeneous in macrotexture; pronounced conchoidal fracture; brilliant vitreous lustre. This type closely resembles the coal constituent vitrinite in general appearance. It does not appear to be readily susceptible to oxidation.

Davidite of this type occurs embedded in a segregation lens of brown colored calcite contained in granulite at the Six Kangaroos Lease, midway between Mt. Isa and Cloncurry. It is associated with minor amounts of bright green actinolite and small sandy patches of pale pink scapolite, together with a few scattered grains of ilmenite and chalcopyrite.

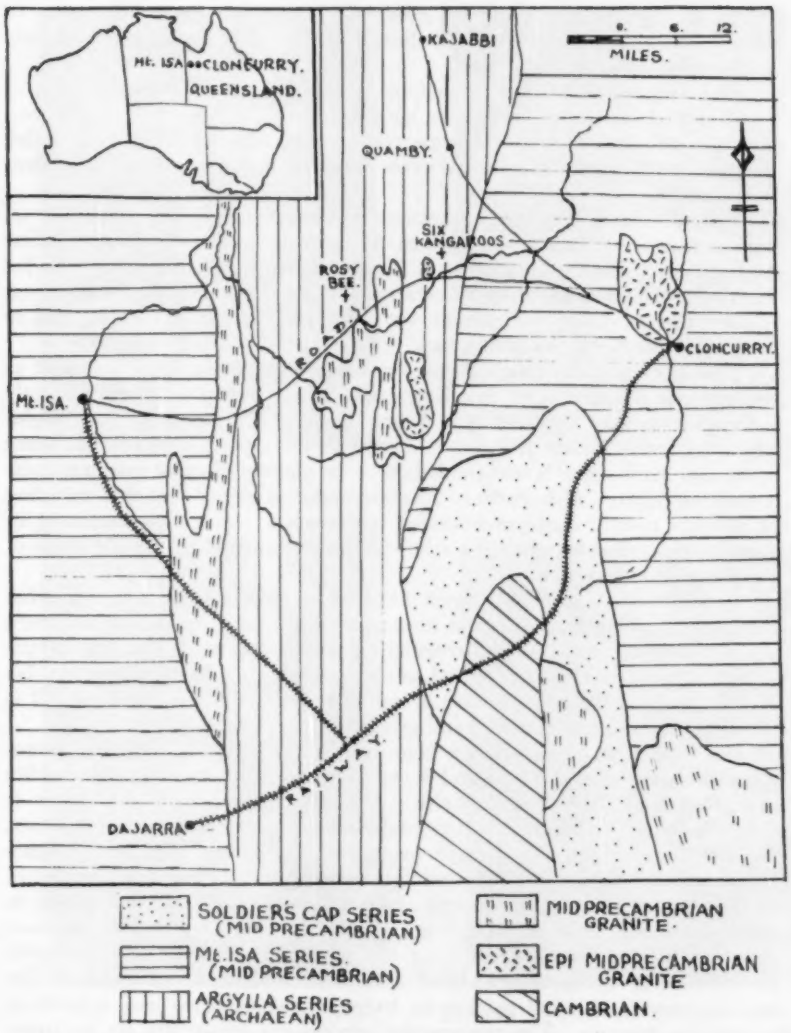

FIG. 1. Locality map.

The mineral takes a good polish and is grayish white in reflected light; it differs in this respect from the gray davidite of Radium Hill, South Australia but like these is quite isotropic and metamict. Davidite of this type in places is veined with very fine quartz stringers containing small grains of hematite.

Under high magnification the otherwise homogenous mineral is seen to contain countless exsolution (?) bodies of ilmenite which may exhibit a subgraphic texture (Fig. 2).

Etch tests with standard reagents gave negative results in each case.

A careful search for inclusions, such as sphene, pyrite, chalcopyrite, and molybdenite, such as occur in some South Australian davidites (10) failed to reveal the presence of minerals other than the ilmenite and hematite mentioned above.

Type 2.—Steel gray in color, macroscopically homogeneous, markedly irregular fracture. This type occurs as eluvial fragments, some showing a few crystal faces, between Quamby and Kajabbi north of Cloncurry, and in the vicinity of Dajarra south of Cloncurry. In each instance the neighboring country rock is schist, and, though not found *in situ*, the davidite appears to have been weathered out of this rock.

This steel gray davidite also takes a good polish though not as perfect as the vitreous davidite from Six Kangaroos. In reflected light it is slightly more grayish than those of type 1 but the color difference is very slight. Minute ilmenite bodies are also contained in the type 2 davidite. In some specimens the ilmenite is more abundant in the vicinity of small fractures some containing quartz and hematite. The impression is gained that this crowding of ilmenite toward incipient fractures represents a segregation unmixing of ilmenite from davidite with the solute (ilmenite) migrating toward areas of strain within the solvent.

Type 3.—Dark gray to grayish black on a fresh surface and somewhat mottled due to the presence of at least two constituents that can be discerned vaguely with the unaided eye; irregular to hackly fracture. This type occurs as a dissemination in granulite and as eluvial pieces midway between Mt. Isa and Cloncurry (Rosy Bee Lease) a few miles west of Six Kangaroos. It is prone to alteration to carnotite and gummite.

Davidite of this type takes a poor polish. In reflected light its heterogeneous character is apparent and it resembles, in many respects, the davidite from Radium Hill, South Australia. Although referred to as davidite it is clearly a mineral composite. It is composed of three constituents: davidite, ilmenite, and hematite in the approximate ratio 50 : 40 : 10. The davidite areas are distinctly gray in reflected light and exhibit the lowest reflectivity of all three types. It is quite isotropic and homogeneous and does not appear to carry exsolution ilmenite though an occasional grain of hematite has been observed in it. The ilmenite is of the purplish gray type and distinctly pleochroic. It contains orientated exsolution magnetite (Fig. 3). The davidite occurs as round patches or irregular shaped areas and appears to replace the ilmenite. The replacement process has apparently set up stress within the ilmenite resulting in the development of a series of radial fractures, in most instances, where davidite "invades" the ilmenite (Fig. 4).

An interesting feature of the ilmenite of type 3 davidite, viewed under crossed nicols, is the presence of a continuous fringe exhibiting grayish purple polarization color, which grades quickly into the normal light gray polarization color of ilmenite (Fig. 5).

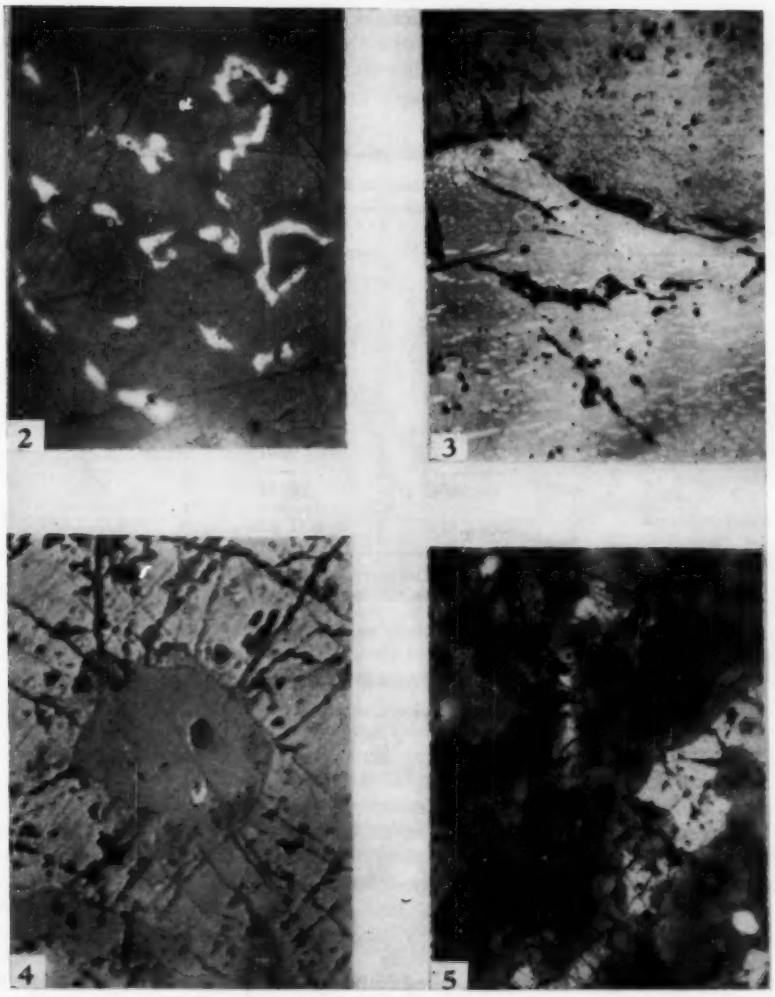

FIG. 2. Sub-graphic intergrowth of ilmenite (white) in davidite (gray). Dajarra, south of Cloncurry. Positive phase contrast photomicrograph × 600.

FIG. 3. Orientated exsolution bodies of magnetite (white) in ilmenite (light gray) in contact with an area of davidite (darker gray). Rosy Bee Lease, Cloncurry. Positive phase contrast photomicrograph × 600.

FIG. 4. Davidite (gray) replacing ilmenite (light gray) and setting up radial stress fractures in the ilmenite. Rosy Bee Lease, Cloncurry. × 50.

FIG. 5. Davidite (black) replacing ilmenite which is developing radio-active halos. Rosy Bee Lease, Cloncurry. X-nicols × 500.

Professor Ramdohr (personal communication) states that this fringe is a radio-active halo produced within the ilmenite by bombardment from the davidite metasome. Ramdohr further states that radio-active halos have not previously been observed in an opaque ore.[1]

CHEMICAL COMPOSITION

Chemical analyses of the three davidite types gave the following results:

	1	2	3
TiO_2	46.72	54.03	35.42
FeO	18.33	15.61	18.22
Fe_2O_3	16.53	12.43	15.17
U_3O_8	6.41	2.17	20.16
V_2O_3	2.88	2.26	3.10
Al_2O_3	1.05	3.53	1.61
SiO_2	6.02	3.29	5.25
CaO	1.71	4.50	1.84
MgO	0.17	1.20	0.14
MnO	0.61	0.25	0.63
Cr_2O_3	—	0.04	—
	101.54	100.43	99.31
	S.G. 4.32	S.G. 4.26	S.G. 4.89

1. Davidite type 1, Dajarra, south of Cloncurry. Analyst G. T. See.
2. Davidite type 2, Six Kangaroos Lease, midway between Mt. Isa and Cloncurry. Analyst G. T. See.
3. Davidite type 3, Rosy Bee Lease, midway between Mt. Isa and Cloncurry. Analyst G. T. See.

TABLE I

RADIO-ACTIVITY MEASUREMENTS ON AN AUSTRONIC β. COUNTER

Davidite type 1	4,150 counts/gram/minute
Davidite type 2	872 c/g/m
Davidite type 3	13,740 c/g/m

Spectrographic analyses on samples from types 1 and 3 were compared with an analysis of a sample from the type locality Radium Hill, South Australia. The results are given in the following table.

X-RAY ANALYSIS

The three davidites were studied by means of X-ray diffraction using an 11.46 cm diameter camera, and CuKα radiation with powder mounted on glass fibre supports.

No pattern could be obtained until the specimens were subject to heat treatment for 12 to 24 hours at temperatures above 700° C. As is the case

[1] Editor: Three specimens of polished surfaces of ores for some time have been in the collections of the Laboratory of Economic Geology of Yale University, which display such radio-active haloes. One specimen is from the Mary Kathleen, and another, davidite, from Radium Hill.

TABLE II

SPECTROGRAPHIC ANALYSES OF DAVIDITES FROM MT. ISA–CLONCURY AND RADIUM HILL, SOUTH AUSTRALIA

	1	2	3
Sn	×	×	×
Pb	×	×	×
Zn	×	×	×
Ge	–	–	–
As	×	–	–
Mo	×	–	–
Ta	–	–	–
Be	×	×	×
Cd	–	–	–
In	×	×	×
Au	–	–	–
Ag	×	×	×
Cu	×	×	×
Sb	×	×	×
Zr	×	×	×
Ru	–	×	×
Rh	–	×	×
La	×	×	×
W	×	×	×
Cr	×	×	×

×: present –: absent

1. Davidite, Radium Hill, South Australia.
2. Davidite (type 1), Dajarra.
3. Davidiate (type 3), Rosy Bee Lease.

with other davidites this heat treatment restored crystallinity from the metamict state in which this mineral always appears to exist (10). The resulting pattern was clearly marked.

In Table III the "d" values for the three davidite types are given together with relative intensities estimated by visual inspection. The results are compared with the standard "d" and "I" values for davidite as given in the A.S.T.M. index. A fairly close agreement between all four specimens was obtained.

Some of the lines of the davidite standard are ascribed by the A.S.T.M. index to impurities. A number of additional lines appear in specimen 2 from Dajarra; these are consistent with one or other of the aluminum silicates, which are apparently present though not visible under the microscope. In addition, a number of the "I" values show a substantial variation. This is probably due to incipient oxidation during heat treatment.

Some of the "d" values are much the same as those for ilmenite (*) and this is to be expected as ilmenite is an important "constituent" of some of the davidites and in others is an intimate associate.

DISCUSSION

In only one of the five known occurrences of davidite in the Mt. Isa-Cloncurry District is intrusive igneous rock visible—an unstressed tourmaline

pegmatite near Quamby south of Kajabbi. A systematic search for radioactive minerals both by inspection and with the aid of a scintillometer failed to reveal the presence of such minerals in the pegmatite. On the other hand davidite occurs *in situ* in granulites and schists in each of the other localities

TABLE III

X-RAY DIFFRACTION DATA, MT. ISA–CLONCURRY DAVIDITES

1		2		3		4	
"d"	"I"	"d"	"I"	"d"	"I"	"d"	"I"
1.44	(10)	1.44	(9)			1.44	(9)
		1.48	(1)				
1.51	(3)*	1.50	(1)			1.51	(1)
1.53	(1)			1.54	(10)	1.55	(2)
1.54	(1)			1.57	(3)	1.58	(2)
1.60	(10)*	1.59	(9)*	1.62	(9)*	1.60	(9)*
						1.65	(1)
1.68	(4)	1.69	(1)	1.69	(7)	1.69	(8)
1.71	(4)	1.70	(10)*			1.71	(8)
1.77	(9)	1.79	(4)	1.77	(9)	1.78	(2)
						1.81	(8)
		1.89	(2)	1.86	(6)*	1.85	(2)
1.91	(2)	1.91	(2)	1.89	(6)	1.92	(2)
1.96	(3)			1.96	(9)	1.97	(1)
		2.02	(1)*			2.04	(4)*
				2.07	(2)	2.09	(1)
2.14	(9)	2.12	(4)			2.15	(1)
				2.18	(2)	2.20	(4)
2.25	(10)	2.23	(8)*			2.26	(7)
		2.36	(1)	2.39	(1)		
		2.41	(2)				
2.43	(6)	2.46	(6)	2.46	(3)	2.44	(3)
2.47	(9)	2.49	(2)			2.49	(7)
2.64	(4)	2.68	(1)	2.62	(4)	2.65	(2)
				2.68	(1)		
2.75	(4)*	2.74	(1)*	2.73	(8)*	2.77	(–)*
		2.83	(2)				
2.84	(4)	2.87	(8)	2.86	(2)	2.86	(10)
2.90	(10)	2.90	(1)			2.91	(–)
2.99	(4)	3.03	(3)			3.03	(–)
3.05	(6)			3.09	(7)	3.08	(3)
3.24	(5)	3.21	(4)	3.21	(7)	3.25	(6)
		3.34	(9)				
3.40	(10)			3.42	(10)	3.42	(6)
		3.50	(9)				
				4.11	(5)		

1. Davidite from Six Kangaroos Lease, midway between Mt. Isa and Cloncurry.
2. Davidite from vicinity Dajarra.
3. Davidite from Rosy Bee Lease, midway between Mt. Isa and Cloncurry.
4. Davidite standard A.S.T.M. index.

but dispersed and in small amounts. In fact there is no evidence, in most instances, of igneous activity even at depth (e.g. thermal metamorphic effects, quartz veins, etc.). One is forced to consider a geosynclinal and subsequent regional metamorphic origin for the davidites and associated minerals.

Edwards (3, 2) envisages an underlying zone of igneous rock of regional dimension to which he ascribes some of the mineralization and the scapolitization of the Mt. Isa-Cloncurry District. But, as pointed out by Sundius (9) and Ramberg (8), it does not seem necessary to invoke an igneous source for the development of scapolite. As Ramberg (8) states, "Numerous studies of regionally metamorphosed limestones have shown that (such) a nonmetasomatic origin of scapolite is rather common."

The unusual wide variety of trace elements (Table II) present in the various davidites is an interesting feature. Some of these elements (Ru, Rh) belonging to the platinoid group are characteristic of the ultrabasic rocks. The primary origin of the others is in the acidic rocks. There is some reason to suppose that the sediments of the pre-metamorphosed Argylla Series were derived from very diverse terrains yielding *inter alia* equally diverse elements or mineral particles.

These occurrences of davidite in a highly metamorphosed area and apparently of regional metamorphic origin contrast with the two other recorded occurrences. At Radium Hill (5, 7) the davidite mineralization follows closely upon the intrusion of acid pegmatites and sodic aplites to which the davidite appears to belong. In Mosambique (1) the davidite has been injected into shear planes in epidiorite along with calcite, scapolite, ilmenite, apatite and minor amounts of molybdenite; a metasomatic origin is indicated. The interesting paragenesis at Mosambique: davidite, scapolite, calcite, ilmenite is repeated at Cloncurry (Six Kangaroos Lease) though it would seem that the origin of the two occurrences differ in some respects.

From a mineralogical standpoint two interesting features emerge: the possible existence of an eutectic between davidite and ilmenite (Fig. 1) and the unusually high U_3O_8 content of the davidite composite from the Rosy Bee Lease (Analysis No. 3 q.v.). When it is considered that the composition of the material analyzed was essentially 50 percent davidite and 40 percent ilmenite and the overall U_3O_8 content is 20.16% with a proportional increase in the amount of β radiation (Table 1), the presence of another highly uraniferous isotropic mineral might be suspected, e.g. uraninite. The X-ray pattern, however, does not indicate this. It remains to be seen whether the associated ilmenite (Figs. 3, 4 and 5) is substantially uraniferous. Ilmenite containing 0.20% U_3O_8 has been recorded (6). An investigation of the ilmenite from the Rosy Bee Lease is currently being carried out.

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KENSINGTON, SYDNEY,
Oct. 8, 1956

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BURNT HILL WOLFRAMITE DEPOSIT, NEW BRUNSWICK, CANADA

IRIS VICTOR

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ABSTRACT

Wolframite ore in the Burnt Hill Tungsten deposit occurs in a series of steeply inclined, more or less parallel quartz-topaz fissure veins. These veins cut across interbedded spotted schists, phyllites, quartzites, and quartz-biotite rocks. A Devonian granite batholith is exposed approximately one mile north.

An unusual and abundant suite of minerals is unevenly distributed in the fissure veins. These minerals may be divided into two main groups: 1, early vein minerals consisting of beryl, quartz, wolframite, biotite, topaz, cassiterite, molybdenite, apatite, muscovite, and scheelite. 2, later vein minerals consisting of the metallic minerals, arsenopyrite, sphalerite, pyrrhotite, pyrite chalcopyrite, galena, and native bismuth. The late nonmetallic minerals are fluorite, prochlorite, and calcite, and the alteration minerals consist of clinochlore and cryptocrystalline muscovite polymorphs. The early-formed high-temperature minerals such as beryl, topaz, wolframite, cassiterite, and molybdenite, are extensively replaced by sulfides that crystallized later. Native bismuth, which must have crystallized below 271.3° was the last metallic mineral to crystallize.

The deposit is believed to be a transition from hypothermal to mesothermal mineralization.

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INTRODUCTION

THE properties of the Burnt Hill Tungsten Mines Ltd. are located in York County, New Brunswick, Canada. They comprise approximately one and a half square miles, near the junction of Burnt Hill Brook and the Southwest Miramichi River.

Wolframite ore occurs in a series of more or less parallel high temperature quartz-topaz veins, which cut the surrounding phyllites and spotted schists almost at right angles to the planes of schistosity. The schists, phyllites, and quartzites are Ordovician or earlier in age (Canadian map 910 A, 1949). The veins dip from 60° to 85° to the northeast and strike about N 50 W. They are commonly branching and anastomosing. Veins vary in width from a fraction of an inch to over four feet, and are commonly spaced from two inches to six feet apart. Some are several hundred feet long.

The minerals are unevenly distributed in the veins. There is no distinct banding of minerals, but wolframite, molybdenite, and beryl crystals may grow out from the sides of the veins and produce comb structures.

The ore mineralization is controlled by fracturing rather than by the type of country rock. Quartzite is interbedded with the spotted schists and phyllites. The mineralized veins in the quartzite are more numerous and irregular than those in the schists, whereas many quartz stringers in the quartzite also contain ore mineralization. The quartzite contains more wolframite than the schists and phyllites because of the additional fracturing. An earlier set of quartz veins which is parallel to the planes of schistosity of the phyllites and spotted schists appears to have no wolframite mineralization. Numerous breccia and gouge zones occur, which have the same attitude as the wolframite-bearing quartz-topaz veins. The gouge is composed primarily of 3T muscovite.

A large Devonian granite body is located approximately one mile north of the mine. As the granite contact is approached, the rocks grade from spotted schists to highly metamorphosed spotted schists and finally to banded gneiss. Aplite and greisen veins are located near the granite. The Burnt Hill Tungsten deposit bears a remarkable similarity to the wolframite deposits in Burma, Malaya, and the Kiangsi province in China. Most of the Kiangsi tungsten deposits are classified as pegmatitic hypothermal deposits (10).

The high temperature origin of the Burnt Hill deposit is indicated by the presence of many high temperature minerals such as beryl, topaz, wolframite, cassiterite, and molybdenite. The presence of water is indicated by the abundance of hydrous minerals. The paragenesis of the ore indicates that there were various stages of mineralization with the later minerals replacing many of the earlier ones.

History.—In 1868, Dr. Charles Robb discovered molybdenite in the veins near the mouth of Burnt Hill Brook. The property was staked for molybdenite in 1908. In 1910, Dr. T. L. Walker observed that wolframite occurred with the molybdenite. A mill to concentrate wolframite was erected on the property in 1917. A 167 foot shaft was sunk and 567 feet of drifting was completed on the 40 and 150 foot levels. However, in December, 1917, the mine was closed due to the fact that the mill equipment was not suitable to concentrate the complex wolframite and sulfide ore.

The property was idle for 36 years. In 1953, a new mine was started 1,310 feet east of the old workings by the Burnt Hill Tungsten Mines Ltd. that now operates the property. The development work from 1953 to August 1955 includes 3,646 feet of drifting and cross cutting, and surface and underground diamond drilling. The surface diamond drill went down to a depth of 495 feet. A 150-ton mill to concentrate the wolframite ore was completed in 1955. During the summer of 1955, wolframite concentrates were shipped.

Location.—The properties of the Burnt Hill Tungsten Mines Ltd. are located in York County, New Brunswick, Canada, near the junction of the Burnt Hill Brook and the southwest Miramichi River. The mine is on the north slope of a hill which rises 650 feet above the south bank of the Miramichi River. The mine is approximately 65 miles northeast of Fredericton, the

capital of New Brunswick, and 16 miles from the Maple Grove Station. A bush road from the Maple Grove Station to the mine is open all year. The mine is on the properties of the International Pulp and Paper Company.

GEOLOGY

Structural Features

Fissure Veins.—The chief veins are mineralized tension fractures. They dip from 60° to 85° NE and strike about N 50 W, cutting the schistosity almost at right angles. Some are several hundred feet long and range in width from a fraction of an inch to over four feet. The veins are more or less parallel and are commonly spaced from two inches to six feet apart.

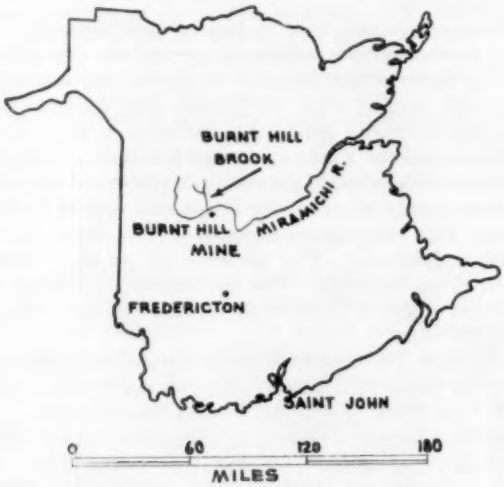


FIG. 1. Sketch map of New Brunswick showing location of Burnt Hill Tungsten Mine.

They run through the spotted schists, phyllites and quartzite, and commonly branch and anastomose. Some are frozen to the wall rock and others break free due to a thin layer of slickensided chlorite between the vein and the wall rock.

The veins in the quartzite are more numerous and irregular than those in the schists; they are commonly en echelon, and pinch out at the top and bottom. Numerous quartz stringers also contain ore mineralization. The majority of the minerals in the veins are well crystallized. Quartz, topaz, beryl, wolframite, cassiterite, arsenopyrite, pyrite, molybdenite, fluorite, prochlorite, and biotite all form euhedral crystals.

The veins are composed primarily of massive quartz and $\frac{1}{4}''$ to $1''$ wide

topaz crystals. The other minerals are unevenly distributed in the quartz. The minerals found in the fissure veins in relative order of abundance are: quartz, topaz, pyrrhotite, prochlorite, pyrite, wolframite, arsenopyrite, molybdenite, fluorite, beryl, biotite, clinochlore, muscovite, cassiterite, scheelite, chalcopyrite, native bismuth, apatite, calcite, sphalerite, and galena.

There are many small ($\frac{1}{8}$" to 6") irregular cavities in the fissure veins, which are commonly filled with fluorite crystals coated with prochlorite. Drusy quartz and pyrite crystals also occur in the vugs.

The veins have no distinct banding, but quartz, wolframite, beryl, and molybdenite crystals commonly grow out from the sides of the veins and produce comb structures. These minerals all crystallized early. Their occurrence along the walls of the veins was apparently due to preferred nucleation as the hydrothermal solutions were chilled along the contact with the wall rock.

Faults.—There are numerous breccia and gouge zones that have the same attitude as the wolframite bearing quartz-topaz veins. The gouge zones are from one inch to two feet wide. They contain fragments of quartz vein and wall rock partially cemented by 3T muscovite and prochlorite. 3T muscovite is the most abundant mineral in the gouge zones.

Some of the larger faults dip to the south at angles of only 15° to 25°. Large laminated plates of calcite, some over a foot long, commonly occur in these faults. The calcite is strongly deformed and recrystallized, which indicates that there was additional movement after the deposition of the calcite crystals.

Bedded Veins.—Narrow quartz veins approximately one inch wide have formed parallel to the planes of schistosity of the spotted schists and phyllites. These veins formed before the mineralized tension fractures, and do not appear to contain ore mineralization. The two sets of veins are almost at right angles to each other. The fissure veins cut across the bedded veins.

Bedding.—Metamorphosed rock consisting mainly of quartz and biotite is interbedded with the spotted schists, phyllites, and quartzites. The texture of the quartz and biotite grains is coarser than those in the schists. Biotite is commonly concentrated along the interface between the schist and quartz-biotite rock. The bedding is approximately parallel to the schistosity of the schists and phyllites.

Rock Types

Spotted Schists.—The dark gray spotted schists and phyllites strike about N 20 E and dip 60° NW. The "spots" in the schists contain crystal aggregates of biotite or chlorite. They are mostly isolated and rounded but crystal outlines can often be observed. They are mostly 1.0 mm long. The relict crystals appear to contain the same minerals as the schist but the concentration of biotite is generally greater in the relict crystals than in the surrounding schist (Fig. 2). These relict crystals suggest that the earlier formed rock may have contained pheoncrysts or porphyroblasts, which upon subsequent metamorphism were replaced mainly by aggregates of biotite

crystals. The relict crystal outlines are often surrounded by metallic grains which are 0.02 mm in size.

Pyrite and pyrrhotite replace the schist. The pyrite forms automorphic crystals. Skeleton and automorphic pyrite crystals vary in size from approximately 0.2 mm to 0.4 mm. Fluorite also replaces the schist and forms rounded areas similar to the aggregates of biotite crystals.

Quartzite.—The quartzite is a light to medium gray in color. The mineralized fractures in the quartzite are commonly en echelon and very irregular

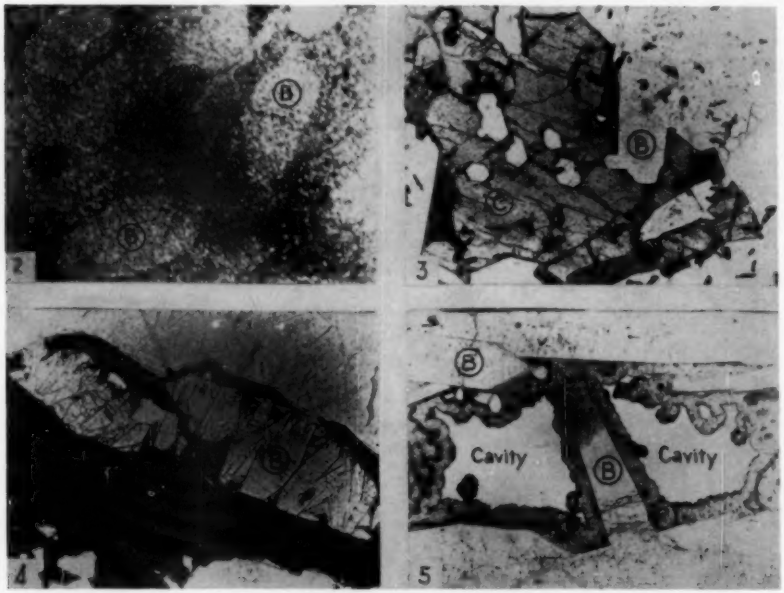


FIG. 2. Spotted schist containing aggregates of biotite crystals (B), which preserve relict crystal outline of a former mineral. × 18, ×-nicols.

FIG. 3. Cassiterite (C) surrounding beryl crystals (B). Small wolframite crystals 0.1 to 0.2 mm (black) are included in cassiterite and beryl. × 70.

FIG. 4. Molybdenite (black) surrounding and partially replacing beryl crystals (B). × 18.

FIG. 5. Beryl crystals (B) surrounded by prochlorite (P). × 18.

in outline. The quartzite is more fractured than the schists and thus contains more wolframite.

Granite.—A Devonian granite batholith (Canadian Map 910 A, 1944) outcrops approximately one mile north of the mine. As the granite contact is approached, the rocks grade from spotted schists and phyllites to highly metamorphosed spotted schists and finally to banded gneiss.

The biotite and feldspars in the granite are greatly altered. Quartz grains

are commonly twinned. Fluorite and apatite occur in the granite. The biotite may contain elongated opaque inclusions, which are concentrated along the cleavage directions of the biotite. These inclusions may be wolframite. Apart from the few black inclusions in the biotite, the granite does not appear to contain ore mineralization. The absence in the granite of most of the minerals that occur in the fissure veins is to be expected if the ore solutions were derived from the end stage fluid portion of the magma. Mineralized quartz veins cut the granite, but they are less numerous than the quartz veins in the surrounding rocks.

Aplite and Greisen.—Aplite and greisen dikes are found in the metamorphic rocks near the granite contact. The dikes strike northwesterly parallel to the fissure veins. Occasionally, a few flakes of molybdenite are seen in the aplite, but most of the aplite is free from the ore minerals found in the fissure veins.

The greisen contains wolframite, cassiterite, and molybdenite. Both the aplite and greisen dikes are much less numerous than the quartz-topaz fissure veins.

ORIGIN OF DEPOSIT

Although typical complex pegmatite minerals such as topaz and beryl are found in the fissure veins, the highest temperature of formation was probably not above 573.1 ± 0.5° C, as quartz crystals which, according to Sosman (14), are typical of alpha quartz, were among the earliest minerals to crystallize. The inversion of alpha to beta quartz occurs at 573.1 ± 0.5° C (13). The paragenesis of the ore clearly indicates that the minerals were not all deposited at the same time. Native bismuth was the last metallic mineral to crystallize. Native bismuth melts at 271.3° C at atmospheric pressure. The presence of other substances would tend to lower the melting point. Since, unlike most minerals, the volume of solid bismuth is greater than liquid bismuth, an increase in pressure would also lower the melting point. Thus, native bismuth must have crystallized below 271.3° C.

The Burnt Hill Tungsten deposit is very similar to the deposits in the Kiangsi province in China, most of which are classified as pegmatitic hypothermal deposits, and the deposits in Malaya and Burma, which are classified as hypothermal (10). Since native bismuth, which crystallizes below 271.3° C, occurs at Burnt Hill, the deposit cannot be classified as hypothermal according to Lindgren's classification. However, the presence of many high-temperature minerals such as beryl, topaz, wolframite and cassiterite, indicates that much of the mineralization may have crystallized within the hypothermal temperature range. Thus, there would be a gradation from hypothermal to mesothermal mineralization as the temperatures of the ore forming solutions were gradually lowered.

A. F. Buddington (3) discusses high temperature mineral association at shallow to moderate depth. The depth is at or below 2,000 to 3,000 feet, and the temperature range is from 300° C to 500° C. He calls these deposits xenothermal deposits. The cassiterite and cassiterite-wolframite deposits of

the Ikuno-Akenobe District in Japan, and Llallagua, Bolivia, Buddington interprets as xenothermal.

Buddington states that in deep high-temperature deposits, the high-temperature minerals such as magnetite, topaz, tourmaline, apatite, specularite, orthoclase, augite, diopside, and phlogopite, are generally well crystallized and aggregates are medium to coarse grained. In high-temperature deposits of shallow to moderate depths, the tourmaline and topaz are commonly fine grained. The cassiterite, which is in part intergrown with specularite, generally has a colloform structure with radiating fibers. Quartz that is associated with the deposit is commonly fine grained, and of a cherty or porcelain-like character, or may even be chalcedonic. Pyrrhotite is rarely present, presumably because of the low pressure and high temperatures. A mineral association of high temperature, moderate to great depth, which has not been found at shallow depths, is that characteristic of complex pegmatites comprising such minerals as alkali tourmalines, beryl, lepidolite, spodumene, or albite.

Most of the minerals in the Burnt Hill deposit are well crystallized and aggregates of crystals are coarse grained. Beryl is present and pyrrhotite is abundant. Thus, it seems unlikely that the Burnt Hill deposit could be classified as a xenothermal deposit.

Unlike Buddington's xenothermal deposits, the tungsten deposits in southern Kiangsi bear a remarkable similarity to the Burnt Hill tungsten deposit. Li and Wang (10, p. 34) give the following description of the Kiangsi deposits.

> The pegmatitic hypothermal veins are almost the only tungsten producing deposits in southern Kiangsi. They are well defined tabular bodies, formed by the filling of pre-existing fissures. They are regular in strike and dip and in lateral and vertical extension. Gangue minerals in these veins include quartz, muscovite, and lithium micas, orthoclase, fluorite, tourmaline, topaz, beryl, albite, sericite, chlorites, and calcite. Primary ore minerals include wolframite, cassiterite, scheelite, pyrite, chalcopyrite, bismuthinite, molybdenite, arsenopyrite, sphalerite, galena, pyrrhotite, native bismuth, magnetite, specularite, tetrahedrite, and stannite. . . . The texture of the tungsten veins is rather coarse. Tabular crystals of wolframite range from 1 to 5 cm. in width and from a few cm. to 30 cm. in length, being commonly 3 to 9 cm. long. Associated minerals such as lithium micas, drusy quartz, orthoclase, cassiterite, fluorite, tourmaline, etc., are also coarse. Fine grained texture is unknown. Massive quartz makes up most of the veins in which all other minerals are embedded.

Although the structure and much of the mineralization of the Burnt Hill deposit are similar to those in Malaya, Burma, and China, the ages of the deposits differ. The igneous rocks associated with tungsten deposits in Malaya, Burma, and China, are late Mesozoic in age (10, p. 22). The granite associated with the Burnt Hill tungsten deposit is Devonian.

Tourmaline is present in the fissure veins in southern Kiangsi. However, in the Burnt Hill deposit no tourmaline has been found. Campbell (4) in his paper on the Tavoy District in Burma reports that not a single crystal of tourmaline has been found in spite of the most assiduous search. Campbell

also writes that in Tavoy, wolframite never occurs in minute crystals, whereas bismuthinite is commonly found in microscopic crystals scattered throughout quartz, giving it a smoky appearance. In the Burnt Hill deposit wolframite rather than bismuthinite occurs in minute crystals scattered throughout quartz, topaz, cassiterite and beryl. X-ray powder patterns were taken of topaz containing wolframite inclusions.

Campbell believes that a silico-aqueous solution from the granite magma carried tungsten, tin, and other metals in solution and it was from this medium that they were deposited in the veins. He does not believe that the Tavoy deposits have a pneumatolytic origin.

In relation to the origin of the Tavoy deposits Campbell writes,

> There is one very interesting mode of development of wolframite. Crystals grow from a few points on the walls in bladed form usually about one eighth inch thick, an inch wide, and as much as a foot long: from these other similar ones develop and so on until perhaps 10 per cent of the total vein space for many feet of its length and depth is occupied by these ramifying crystals. The space is filled with quartz. This is unquestionably the result of crystallization from a solution.

Wolframite crystals occur in a similar manner at Burnt Hill. The comb structure is quite common.

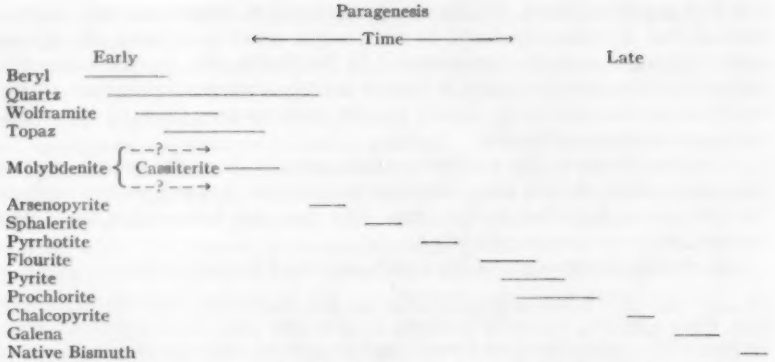
William Jones (7, p. 39) writes, "It is an interesting and significant fact that not in a single tinfield in the world has tinstone been found in situ except near granite or granitic rocks."

Judging from the variety of evidence available, there seems to be little doubt that tin and tungsten deposits are related to acid igneous rocks. However, there is a question as to whether high-temperature tungsten veins are directly derived from the end stage fluid portion of the granitic magma or whether the tungsten-bearing solutions come from depths below the granitic magma, where the intrusion would only serve to provide fracture systems along which the solutions could move into the surrounding rocks. Since the tungsten deposits are found only near acid igneous intrusions, it seems more likely that they were derived directly from the magma rather than from sources below the magma.

Buddington (3) believes that the high melting point of tungsten and its chemical affinity for silicon accounts for its concentration in the end stage of the magma.

In the Burnt Hill deposit, the precipitation of minerals from solutions that had circulated over a considerable time interval is shown by the presence of well crystallized high temperature minerals such as beryl, wolframite, topaz, and cassiterite, which are replaced by later sulfides, and finally, the precipitation of native bismuth, which crystallized below 271° C. The presence of water is illustrated by the abundance of hydrous minerals such as chlorite, muscovite, and biotite.

Kerr (8) believes that tungsten in solution exhibits an affinity for silicon and that probably within the magma, the tungsten is in solution as some salt of silicic acid.



Biotite and *apatite* crystallized early. Minute biotite and wolframite crystals are included in amoeba-shaped apatite masses surrounded by topaz. *Muscovite* appears to have crystallized early. It is in places concentrated along the edges of the veins. *Scheelite* crystallized after wolframite, and often replaces wolframite along its cleavage. Massive quartz surrounds scheelite crystals. *Clinochlore* and cryptocrystalline muscovite polymorphs crystallized after prochlorite.

MINERAL RELATIONSHIPS

Early Vein Minerals

Beryl.—Beryl appears to be the earliest mineral to have crystallized in the deposit. It forms slender pale green radiating crystals, which are commonly concentrated along the margins of the veins. The crystals are generally ¼ inch wide and 2″ long. In Figure 3, cassiterite grows around beryl crystals. The small black wolframite inclusions were formed before beryl or cassiterite. However, crystals and masses of wolframite commonly surround and partially replace beryl crystals. Beryl is much less abundant in the deposit than topaz. Molybdenite generally occurs with beryl crystals, but both minerals also occur separately. Figure 4 shows molybdenite surrounding and partially replacing beryl crystals. Prochlorite lines small cavities between beryl crystals. (Fig. 5.)

Quartz.—Massive milky white quartz is the most common variety found in the fissure veins, but some crystals are found in the veins, which are generally ¼ to ¾ inch wide and 1 to 2 inches long. The quartz crystals are euhedral with the $10\bar{1}0$ faces horizontally striated. They are terminated by two rhombohedrons of unequal development. According to Sosman (14) this form is typical of alpha quartz. The quartz crystals were among the first minerals to crystallize.

Drusy quartz is also found in cavities in the veins. Massive quartz had a long period of crystallization. It continued to crystallize after beryl, wolframite, biotite, topaz, cassiterite, molybdenite, apatite, muscovite, and scheelite.

Wolframite.—Wolframite occurs in long tabular crystals and in masses embedded in the quartz-topaz veins. The crystals range in size from 0.1 mm

to about 10 cm in length. Wolframite crystals are commonly found along the edges and centers of the veins. Like all the minerals in the deposit, the distribution of wolframite is erratic. Although the comb structure is common, wolframite crystals and masses may occur in any part of the veins. T. L. Walker (16) gives the following analysis of the wolframite from the Burnt Hill Area: FeO—16.90, MnO—8.37, WO_3—74.43, Total—99.70.

Wolframite was one of the earliest minerals to crystallize. It has been partially replaced by the later minerals, especially the sulfides. Arsenopyrite, pyrrhotite, pyrite, chalcopyrite, galena, and native bismuth all replace wolframite.

Quartz, topaz, fluorite, beryl, and cassiterite may contain microscopic euhedral crystals of wolframite. The wolframite inclusions cause the enclosing mineral to appear black or smoky in color. Some of the inclusions are slightly corroded and embayed. Topaz appears to contain more included crystals of wolframite than the other minerals. The small, 0.1 to 0.2 mm, wolframite crystals apparently crystallized first, and were later caught up in the crystallization of the other minerals. Figure 6 shows these inclusions. Euhedral beryl crystals are commonly included in the larger wolframite crystals.

Topaz.—Next to quartz, topaz is the most abundant mineral in the deposit. Most of the topaz occurs as prismatic crystals, but some is massive. Many of the crystals form a nearly square prism that resembles andalusite. The topaz crystals occur in a variety of colors. White, straw yellow, yellow, dull green, aquamarine, and smoky topaz crystals have been found. The black or smoky topaz contains wolframite inclusions. The topaz crystals are commonly ½ to 1 inch wide and are usually in aggregates.

In Figure 6, massive topaz surrounds quartz crystals. Here, the quartz appears to have crystallized before the topaz.

Topaz is extensively replaced by later minerals. Fluorite commonly replaces topaz along the cleavage planes, and pyrrhotite and pyrite may almost completely replace topaz crystals.

Cassiterite.—Wolframite appears to have crystallized before cassiterite. Figures 7 and 8 show cassiterite containing microscopic crystals of wolframite 0.1 to 0.2 mm in size. The cassiterite, which contains the small wolframite crystals, grows between two euhedral wolframite crystals. Cassiterite is also found growing on wolframite crystals.

In the literature there is a controversy over whether wolframite or cassiterite crystallized first. This controversy is discussed by Li and Wang (10). Most of the following data are taken from their discussions.

Jones (7) believes that cassiterite always crystallizes before wolframite. Campbell (4, p. 518), however, believes that wolframite crystallized before cassiterite.

J. C. Brown (1) writes,

> I am convinced that in the majority of cases, wolframite is older than the tin ore, Dr. A. M. Heron has arrived at the same conclusion independently. At the same time there is no doubt that cassiterite is present in relatively larger quantities in veins traversing granite than those which pierce sedimentary rocks. This apparent anomaly seems to suggest that temperature alone is not the deciding factor in the case.

Li and Wang (10, p. 14) state that in southern Kiangsi, "Tin ore is quite sparse or entirely absent in veins found in overlying sediments, while those traversing the granite contain cassiterite in relatively large amounts."

H. L. Haag (6) in his paper on Wolframite in Nigeria, also observed that a higher proportion of cassiterite is found near the contact and in the granite, than farther away from the granite.

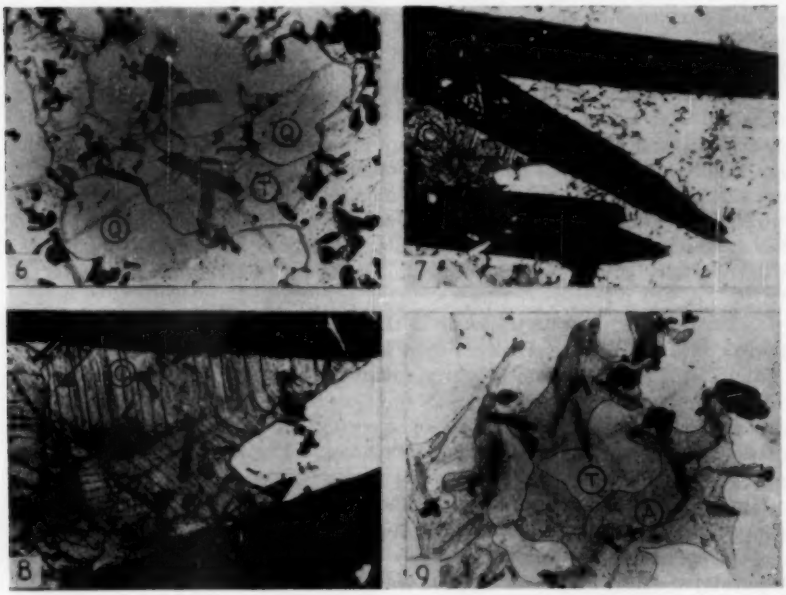


FIG. 6. Quartz crystals (Q) surrounded by massive topaz (T). 01 to 0.2 mm wolframite crystals (black) are included in quartz and topaz and give it a smoky appearance. The edges of the wolframite crystals are slightly corroded by quartz and topaz. × 51.

FIG. 7 AND FIG. 8. Cassiterite (C) crystallized between euhedral wolframite crystals (black). Minute, slightly corroded wolframite crystals 0.1 to 0.2 mm in size (black) included in cassiterite and also in the surrounding quartz and topaz (white). Figure 7 (× 24), Figure 8 (× 51).

FIG. 9. Amoeba shaped apatite (A) surrounded by topaz (T). Shadow crystals of biotite in apatite and topaz. × 51.

J. A. Dunn (5) came to the conclusion that:

. . . wolframite was probably the first mineral to form, but when cassiterite had started to form, it developed much more rapidly, so that the ratio of Sn to WO_3 increased; then gradually and further from the source, wolframite increased in development to a position at which the ratio of Sn to WO_3 was at its lowest."

Li and Wang (10, p. 15) believe that:

. . . within a narrow range wolframite might deposit before cassiterite, or that the temperature or formation of the two minerals might overlap; over a wide range, however, cassiterite would deposit before wolframite, that is, cassiterite is a

higher temperature mineral than wolframite. This apparent anomaly seems to suggest that temperature alone is not the deciding factor and the controlling factors are pressure and relative saturation.

Like most wolframite deposits throughout the world, the veins near the granite at the Burnt Hill deposit contain more cassiterite than those farther away from the granite.

The cassiterite from the Burnt Hill area is generally resin colored with numerous light and dark color bands. The crystals are commonly twinned.

There seems to be no correlation between the presence of cassiterite and fluorite in the Burnt Hill deposit. At the mine fluorite is very common and cassiterite is relatively scarce as compared with wolframite. In the Yuntaishan zone in southern Kiangsi, the amount of cassiterite varies proportionately to that of fluorite (10, p. 37–38).

Molybdenite.—Molybdenite crystallized early and is quite abundant in the fissure veins. It crystallized after wolframite and beryl, but before arsenopyrite and the rest of the sulfides. Molybdenite crystals are generally $\frac{1}{2}$ to 1 inch in size. Massive quartz commonly surrounds and partially replaces molybdenite crystals, and arsenopyrite commonly replaces it along its cleavage. Where massive arsenopyrite crystallized around molybdenite, it commonly caused the molybdenite crystals to be strongly deformed.

Apatite.—Apatite occurs as both crystals and masses. Figure 9 shows masses of amoeba-shaped apatite in topaz. Under short wave ultra violet light, apatite fluoresces a deep yellow color. The fluorescent apatite was identified by X-ray powder patterns. Fluorescent apatite is not abundant in the Burnt Hill deposit.

Muscovite.—Muscovite crystallized early and is in places concentrated along the edges of the veins. The muscovite is either white or very pale pink in color and is coarse grained. Cryptocrystalline muscovite crystallized later.

LATER VEIN MINERALS

Metallic Minerals

Arsenopyrite.—Arsenopyrite, which is quite abundant in the fissure veins, is generally massive but crystals also occur. Massive arsenopyrite is commonly associated with pyrrhotite and pyrite, but arsenopyrite crystallized earlier. Arsenopyrite is commonly found between euhedral wolframite and molybdenite crystals and partially replaces these minerals. The later sulfides including sphalerite, pyrrhotite, pyrite, chalcopyrite, and galena commonly replace arsenopyrite.

Sphalerite.—Sphalerite contains dot-like inclusions of chalcopyrite and pyrrhotite, which may follow the cleavage and twinning directions of sphalerite. Some of the inclusions contain centers of pyrrhotite and irregular rims of chalcopyrite. There is a transition from rounded inclusions to typical fissure veins of chalcopyrite in the sphalerite. The inclusions are mostly non-uniform in size and irregular in distribution. Although sphalerite and chalcopyrite are capable of forming a eutectoid intergrowth (2), the transition from rounded inclusions to fissure veinlets indicates that the texture is pseudo-euctoid and was caused by replacement. L. P. Teas (15) studied numerous sphalerite specimens showing various inclusions of chalcopyrite and concluded that chalcopyrite replaced the sphalerite.

The chalcopyrite rims around pyrrhotite inclusions were probably formed by the partial replacement of the pyrrhotite inclusions by chalcopyrite. Chalcopyrite replaces pyrrhotite in other parts of the deposit.

Pyrrhotite.—Pyrrhotite is the most abundant metallic mineral in the deposit. It has a high magnetic intensity, and is massive and granular. Pyrrhotite generally replaces most of the earlier formed minerals such as beryl, topaz, wolframite, molybdenite, and arsenopyrite. It is one of the few minerals in the deposit that does not form crystals. Irregular veins of concentric and radiating pyrite are found in the massive pyrrhotite. Pyrrhotite is also replaced by chalcopyrite, galena, and native bismuth. Fluorite fills cracks in pyrrhotite, and there is evidence of some replacement.

Pyrite.—Pyrite appears to have crystallized late. Pyrite crystals coat fluorite crystals in the vugs. The crystallization periods of pyrite, fluorite, and prochlorite overlap. Massive pyrite replaces most of the early formed minerals. Pyrite also replaces the metamorphic rocks. Automorphic pyrite crystals are commonly found in the schists and quartz-biotite rock. There is a transition from irregular masses of pyrite replacing the schist to automorphic pyrite crystals.

Irregular veins of concentric and radiating pyrite occur in massive pyrrhotite along fractures. Shrinkage cracks do not occur in the colloform pyrite. The spheroidal banding in the pyrite is probably due to diffusion rather than surface tension.

Chalcopyrite.—Chalcopyrite occurs less commonly than pyrrhotite, arsenopyrite, pyrite, or molybdenite, all of which are abundant. Chalcopyrite is always massive. It commonly occurs as replacement veinlets in many of the earlier formed minerals. It readily replaces wolframite, molybdenite, arsenopyrite, sphalerite, pyrrhotite, and pyrite, and is replaced by native bismuth and galena.

Galena.—Galena is scarce in the fissure veins, and generally forms a graphic intergrowth with native bismuth. The graphic intergrowth appears to be produced by native bismuth replacing galena.

Native Bismuth.—Native bismuth was the last metallic mineral to crystallize in the deposit and is not abundant. Bismuth replaces galena but their periods of crystallization may overlap slightly. Native bismuth commonly replaces fluorite, wolframite, molybdenite, and arsenopyrite. Pyrrhotite and chalcopyrite are also replaced by native bismuth, but not as much as fluorite and galena.

Late Nonmetallic Minerals

Fluorite.—Fluorite, which is common, was one of the last non-metallic minerals to crystallize, and replaces most of the earlier formed ones. Topaz is readily replaced along its cleavage by fluorite. Fluorite occurs as both crystals and masses; the crystals generally occur in vugs. Pink, rose, purple, blue, white, yellow, and pale green fluorite occur. Single crystals are commonly of two different colors. In the vugs, the fluorite crystals may be coated with prochlorite and pyrite crystals.

Figure 10 shows wolframite and biotite crystals in fluorite. The included crystals cut across the cleavage of the fluorite and are corroded, espe-

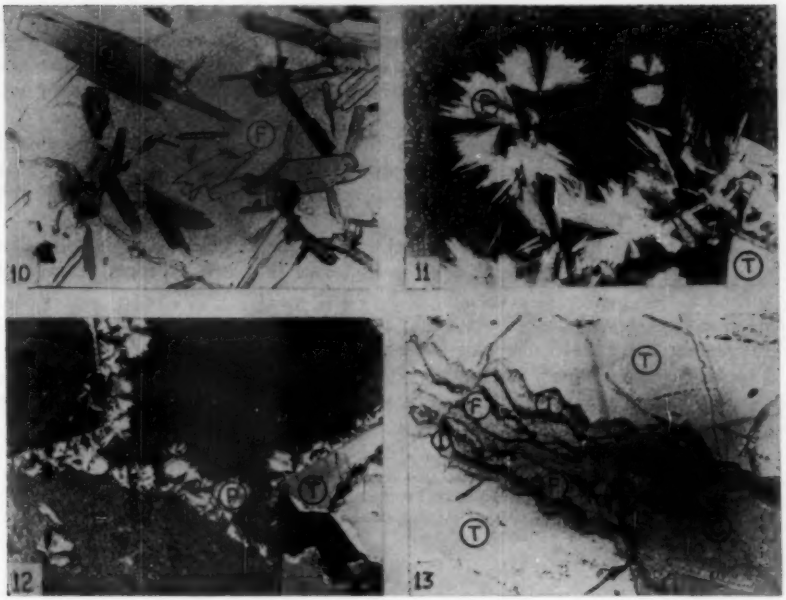


FIG. 10. Wolframite crystals (black) and biotite crystals (B) surrounded by fluorite (F). The edges of the wolframite crystals are partially corroded. × 51.

FIG. 11. Radiating, 0.3 to 0.5 mm, prochlorite crystals (P) surrounding topaz crystal (T). Prochlorite crystals are surrounded by cryptocrystalline clinochlore (C) × 51, ×-nicols.

FIG. 12. Prochlorite crystals (P) surrounding topaz crystals (T). Prochlorite in center of picture follows outline of a mineral which has been completely replaced by cryptocrystalline clinochlore (C) × 21, ×-nicols.

FIG. 13. Topaz crystal (T) being replaced by irregular vein of clinochlore (C), fluorite (F) and cryptocrystalline muscovite (I). × 51.

cially the wolframite. Fluorite is commonly replaced by galena, native bismuth, and clinochlore.

Chlorophane.—The pink variety of fluorite is chlorophane. It is phosphorescent and fluorescent under short-wave ultra-violet light. It also exhibits thermoluminescence and triboluminescence. Under ultra violet light, the clorophane phosphoresces a bright green color. If the chlorophane is heated in a bunsen burner for a few minutes, it will phosphoresce a brilliant aquamarine color. The chlorophane from Burnt Hill which is a bright pink in color exhibits maximum phosphorescence. The pale pink or deep rose variety is less phosphorescent. The impurities that form the electron traps in the chlorophane apparently influence its color.

Chlorophane is commonly associated in the fissure veins with arsenopyrite and clinochlore. However, it crystallized later than arsenopyrite and is replaced by clinochlore.

Prochlorite.—Prochlorite is abundant and was one of the last minerals to crystallize. It occurs in scaly masses, fan-shaped, and spherical groups of crystals. They range in color from dark green to blackish green and are pleochroic. The cleavage surfaces are slightly pearly. The index of refraction is approximately 1.65.

Spherical and fan-shaped prochlorite crystals commonly form around beryl and topaz crystals. Figure 11 shows spherical prochlorite crystals that formed around topaz crystals. Cryptocrystalline clinochlore surrounds the prochlorite.

In Figure 5, prochlorite lines small cavities between beryl crystals. The side planes of the prochlorite crystals that face the cavities, form botryoidal surfaces.

Scaly masses of prochlorite occur between the quartz-topaz fissure veins. Movement has caused many of these prochlorite surfaces to be slickensided. Prochlorite is commonly associated with fluorite and pyrite. Like clinochlore, the prochlorite does not give a very strong X-ray diffraction pattern. The sample was exposed for ten hours using copper radiation.

LATTICE SPACINGS AND ESTIMATED INTENSITIES IN X-RAY POWDER PICTURES OF PROCHLORITE

Prochlorite (Burnt Hill)		Prochlorite (McMurchy, Z Krist, 88, 423, 1934) (Long Hill, Connecticut)	
d	I	*d*	I
14.01	6	13.6	40
6.91	10	6.9	80
4.619	3	4.65	60
3.504	10	3.48	100
2.803	2	2.80	50
2.605	2	2.55	60B
		2.44	40
2.389	2	2.37	40
2.268	2	2.26	30
2.012	5	2.00	80
1.897	1	1.87	40
		1.81	30
		1.70	20
1.661	1	1.65	20
1.558	5	1.56	70
1.517	3	1.54	70
		1.51	40
		1.46	5
		1.41	40
1.384	1	1.38	80
1.336	1	1.32	20
		1.30	20

Calcite.—Calcite occurs in the faults in two unusual forms. One is buff in color and grows in large flat lamellar plates; some are a foot long. The calcite lamellae have been recrystallized and are commonly bent. The other form of calcite occurs as pearly white foliated masses, that have been much deformed. Under the microscope, crystals exhibit interference figures with

2 V of about ten degrees. The calcite was identified by X-ray powder patterns. After the calcite was deposited in the faults, additional movement caused it to be deformed and recrystallized.

Alteration Minerals

Muscovite Polymorphs.—The X-ray diffraction pattern of the yellow cryptocrystalline mineral from the breccia and gouge zones is mainly a 3T muscovite pattern (Table 1). However, the basal spacing is larger than that of a pure muscovite, and according to correspondence with Dr. Yoder, it is probably a mixed layer structure consisting of a random stacking of muscovite and montmorillonite. There is also a small amount of chlorite present.

Topaz crystals in the Burnt Hill Deposit alter to a cryptocrystalline reddish yellow mineral. The X-ray diffraction pattern of the altered Topaz crystals

TABLE 1

X-RAY DIFFRACTION DATA FOR 3T MUSCOVITE

1. Burnt Hill, New Brunswick, Canada		2. Sultan Basin, Washington	
d A	I	*d* A	I
10.770	91	9.969	>100
7.130 (chlorite)	20		
4.965	52	4.991	53
		4.492	19
4.461	100	4.460	19
4.128	20		
3.880	13	3.873	10
3.595	23	3.596	8
3.330	90	3.331	>100
3.108	32	3.110	10
2.883	20	2.884	16
		2.589	15
2.576	69	2.564	27
		2.499	11
2.453	27	2.457	7
2.381	34	2.384	8
		2.254	5
2.234	22	2.222	4
		2.197	4
2.139	27	2.136	12
2.034	22	2.056	3
		1.999	47
1.970	20	1.966	7
		1.885	2
1.703	18	1.654	10
1.656	27	1.638	3
		1.614	3
1.551	9	1.551	2
1.540 (chlorite)	11		
		1.521	6
1.499	41	1.502	11

1. Cryptocrystalline 3T muscovite from the breccia and gouge zones, Burnt Hill Tungsten Mines, New Brunswick, Canada (Cu K alpha radiation).

2. 3T muscovite from the Sultan Basin, Washington. Specimen described by Axelrod and Grinaldi, 1949. X-ray data, Yoder and Eugster (18) The relative intensities of the *d* values which are based on an arbitrary linear scale are not reliable because of preferred orientations.

(Table 2) shows a mixture of about 70 percent $2M_1$ and 30 percent 1M muscovite. The diagnostic d values for the 1M and $2M_1$ muscovite polymorphs are indicated in Table 2. $d = 3.646$ and $d = 3.071$ show the presence of the 1M polymorph.

TABLE 2

X-RAY DIFFRACTION DATA FOR $2M_1 + 1M$ MUSCOVITE

d (A)	I
10.040	>100
5.021	61
4.480	100
4.128	9
3.966	10
3.888 ($2M_1$)	12
3.736 ($2M_1$)	16
3.646 (1M)	16
3.504 ($2M_1$)	31
3.324	>100
3.207 ($2M_1$)	35
3.071 (1M)	20
2.995 ($2M_1$)	26
2.873 ($2M_1$)	16
2.803 ($2M_1$)	12
2.680	8
2.561	>100
2.459	20
2.389	38
2.251	25
2.139	31
2.065	8
1.998	55
1.732	8
1.696	11
1.653	25
1.500	60

Cu K alpha radiation

The author is grateful to Dr. Hatten S. Yoder, Jr. for his kind cooperation in the interpretation of the muscovite polymorphs.

Clinochlore.—Clinochlore is cryptocrystalline and olive to grass green in color. The index of refraction is approximately 1.59. A broken surface of clinochlore resembles chalcedony in texture, but has a hardness of about three. Clinochlore appears to be formed from the alteration of other minerals. It is mostly impure and gives a very poor X-ray powder patterns. The pattern resembles an X-ray pattern for clinochlore with some of the lines missing. Thus, the clinochlore from Burnt Hill may not be a true clinochlore, but rather a poorly crystallized 7 Å material whose properties are similar to clinochlore.

Topaz crystals are embedded in clinochlore. The clinochlore in places replaces fluorite that had crystallized between the topaz crystals. Clinochlore is also found in the centers of topaz crystals; only the shell of the topaz remains. X-ray powder patterns of clinochlore may show the presence of fluorite.

Figure 12 shows two topaz crystals (T) surrounded by radiating prochlorite crystals. Cryptocrystalline clinochlore (C) surrounds the prochlorite. The prochlorite crystals in the center of the picture follow a distinct crystal outline. Clinochlore has completely replaced this crystal or possibly

LATTICE SPACINGS AND ESTIMATED INTENSITIES IN X-RAY POWDER PICTURES OF CLINOCHLORE

Clinochlore (Burnt Hill)		Leuchtenbergite (Clinochlorite) (McMurchy, Z Krist, 88, 423, 1934) (Philipsburg, Montana)	
d	I	*d*	I
		13.1	60
7.13	10	7.0	90
4.502	2	4.68	90
3.545	10	3.52	100
2.855	5	2.82	50
2.506	4	2.52	80B
2.421	3	2.43	50
2.341	3	2.37	10
		2.25	30
2.047	5	2.00	80
		1.88	30
		1.82	30
		1.69	20
1.670	5	1.66	20
1.554	6	1.56	70
1.521	3	1.53	90
1.494	3	1.50	30
		1.46	20
1.417	1	1.42	10
1.336	1	1.39	80
		1.32	30
1.285	1	1.29	30
1.174	1		

another mineral that had previously replaced the crystal. In this particular case, the only evidence of replacement by clinochlore is the relict outline of the crystal preserved by prochlorite that had formed around it. Clinochlore crystallized after prochlorite.

Figure 13 shows an irregular vein of clinochlore in a topaz crystal. Fluorite and cryptocrystalline muscovite are also present.

CONCLUSION

The Burnt Hill wolframite deposit can be classified as a transition from hypothermal to mesothermal type mineralization. The ore solutions that carried the tin and tungsten were probably aqueous solutions of silicic acid. Silicic acid is a powerful solvent capable of combining with metallic oxides.

Although fluorides of W, Sn, and Si have low melting points, WF_6 boils at 19° C, the halides do not seem to occur in sufficient amounts in the Burnt Hill deposit to account for the transport of W, Sn, and Si in a pneumatolytic condition. The fluorite and chlorite in the Burnt Hill deposit are genetically related to pyrrhotite, pyrite, and chalcopyrite rather than cassiterite or wolframite. Fluorite is present in apatite and topaz, which crystallized early, but only in small amounts.

The paragenesis of the ore clearly indicates that the minerals did not all crystallize at the same time. The replacement of minerals that crystallized

early, such as beryl, topaz, wolframite, and quartz, by pyrrhotite, pyrite, fluorite, chalcopyrite, and clinochlore, is so intense that it commonly obliterates the structure of the earlier minerals.

NEW YORK, N. Y.,
Aug. 20, 1956

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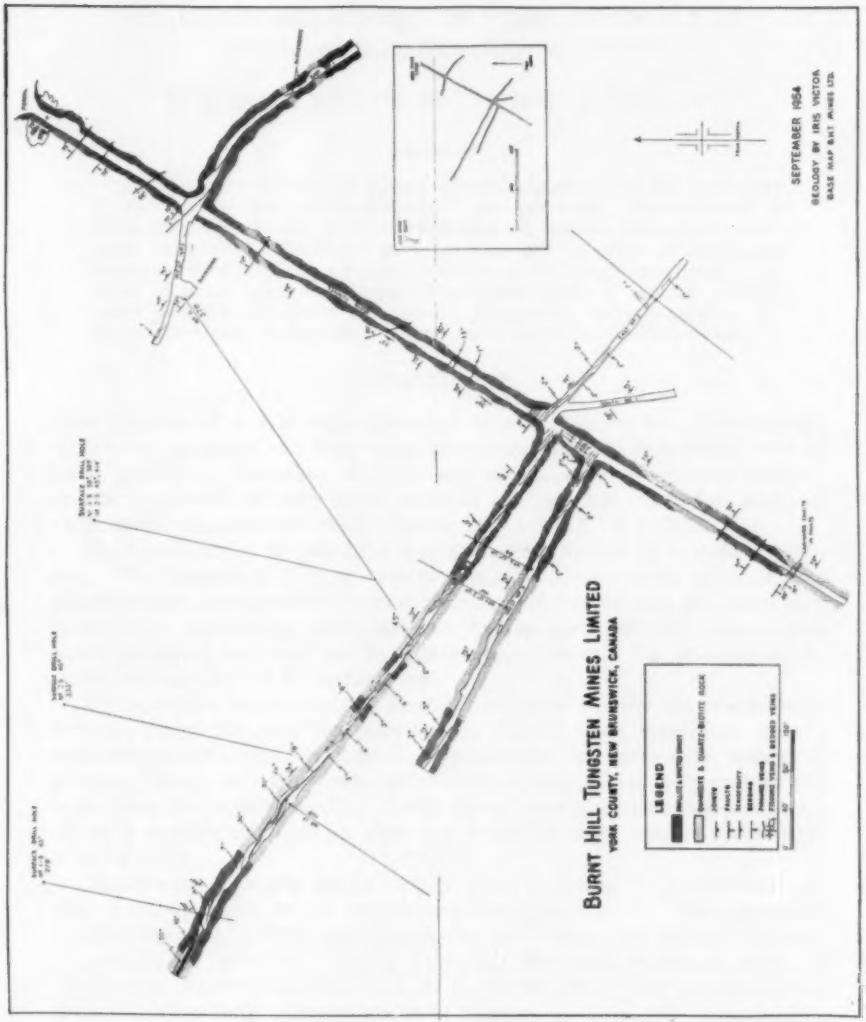
BURNT HILL TUNGSTEN MINES LIMITED
YORK COUNTY, NEW BRUNSWICK, CANADA
LEGEND
SEPTEMBER 1954
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FIG. 14.

STABILITY RELATIONS OF SOME MINERALS IN THE Na_2O–Al_2O_3–SiO_2–H_2O SYSTEM [1]

L. B. SAND, RUSTUM ROY, AND E. F. OSBORN

ABSTRACT

Equilibrium relationships among mineral phases in the low soda part of the system Na_2O–Al_2O_3–SiO_2–H_2O are presented. Assemblages of three crystalline phases in equilibrium with an aqueous phase at elevated water pressure (5,000–30,000 psi) are arranged in order of increasing temperature of stability, with relationships shown diagrammatically by a series of phase triangles. Upper temperature limits of stability at high water pressures are given for analcite, paragonite, hydroxy-sodalite, hydroxy-cancrinite, Na-montmorillonite, and a nepheline hydrate phase.

INTRODUCTION

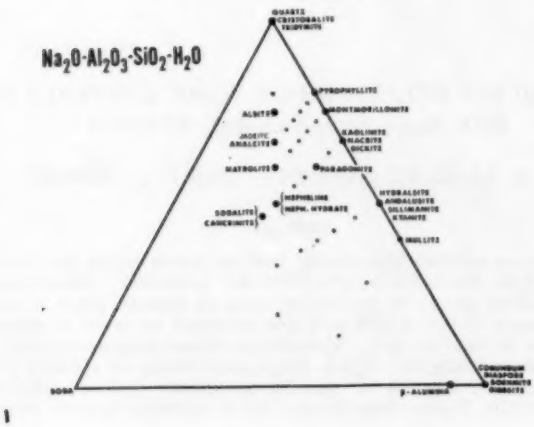
THE hydrates of soda-alumina-silica and of alumina-silica are of widespread occurrence in nature and hence play an interesting and often critical role in many geological processes. A systematic approach to an understanding of phenomena associated with these minerals can be made through a study of phase equilibria in the quaternary system Na_2O–Al_2O_3–SiO_2–H_2O.

Portraying phase relationships in a quaternary system is in itself a problem. The diagram of Figure 1, drawn to show compositions of crystalline phases of particular geologic interest, is derived by considering the quaternary system as a tetrahedron with water as the top apex and with composition points projected upon the base by subtraction of water. The minerals all lie in the low soda half of the tetrahedron.

Of particular interest in this investigation were equilibrium relationships between paragonite and montmorillonite. Under what conditions does a soda-montmorillonite form instead of paragonite, or paragonite instead of montmorillonite, and under what conditions of composition, temperature and water pressure do they coexist? In obtaining some answers to questions such as these, stability relationships were also found for other mineral assemblages in the system.

Four ternary systems can be considered as bounding the quarternary system, three of which are of considerable geologic interest. The anhydrous system Na_2O–Al_2O_3–SiO_2 was investigated by Schairer and Bowen (19, 20). Several studies have been made by Tuttle and Friedman of certain aspects of the system Na_2O–SiO_2–H_2O (22, 5, 6, 9, 10, 25). The system Al_2O_3–SiO_2–H_2O has been reported on most recently by Roy and Osborn (16). Synthesis of phases existing within the quaternary system is discussed by Barrer and White (2) with particular attention to the zeolites.

[1] Contribution No. 55-55, College of Mineral Industries, The Pennsylvania State University, University Park, Pa.



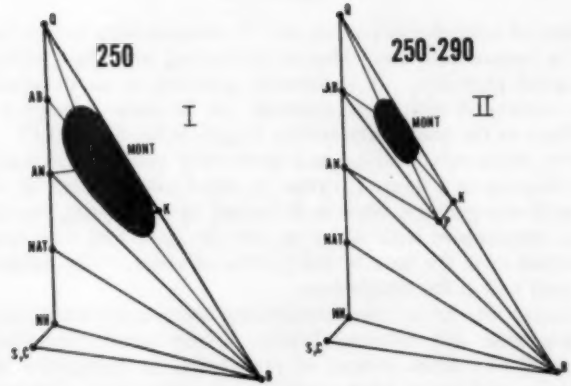


FIG. 1. Crystalline phases in the system Na_2O–Al_2O_3–SiO_2–H_2O with compositions projected on the anhydrous base. Starred points indicate additional synthetic compositions prepared and studied.

FIG. 2. Stability triangles showing three-crystalline-phase assemblages in stable equilibrium with an aqueous phase at 15,000 psi water pressure in the lowest temperature ranges studied. There is some question regarding the stable composition range for the montmorillonites; possibly the areas shown here in black are too large (see text). The triangles in this and succeeding figures are slightly distorted, from relations as shown in Figure 1.

METHOD OF INVESTIGATION

Equipment.—The hydrothermal equipment as described by Roy and Osborn (15) was used in this investigation. Silver-lined bombs were used in all runs except where minerals alone comprised the starting materials.

The silver liner was inserted into the stainless steel bottom of the bomb and was continuous, including the horizontal lip. For the closed bombs pressures were calculated from Kennedy's curves (7). A bomb with the closure outside the furnace was used for obtaining data at temperatures above 550° C. In this case a silver rod was inserted to minimize transfer of material by convection. For studying the decomposition of minerals under various pressures, the "test tube" type of bomb was employed. The grinding apparatus described by Roy and Osborn (15) was effective in accelerating certain reactions. An apparatus also was assembled to study the decomposition of minerals under leaching conditions. It consisted essentially of a double-headed bomb through which CO_2-water mixtures at pressures up to 10,000 psi could be very gradually passed by a control-valve at the outlet.

Materials.—Initial compositions were prepared in several ways: Mixing dry oxides and a sodium salt, preparing glasses, co-precipitating gels, and making "gels" from solutions of metal-organic compounds. The last method, redescribed in detail by Roy (17), proved to be the most satisfactory, and was used in preparing mixtures for almost all runs, excluding the minerals themselves. Soda was added as carbonate except in studying the feldspathoids, when other salts including the hydroxide were used.

Procedure.—Starting materials were wrapped in silver envelopes and placed in the bomb. If it were a closed bomb run, the appropriate amount of water was also added. The bomb was then placed in a furnace at the temperature of the run. The charge was quenched by removing the bomb from the furnace and immediately placing it in cold water.

The phases formed in each run were identified by X-ray diffraction patterns and when possible by petrographic microscope studies. The X-ray patterns were obtained either on a General Electric XRD-3 or a 90° Norelco diffractometer, copper radiation filtered through nickel being used throughout. The very fine-grained nature of the product of a run made phase identification under the microscope uncertain in most cases. The results are based on some 650 runs.

THE CRYSTALLINE PHASES

Of the crystalline phases listed on Figure 1, all can now be easily synthesized except possibly natrolite, nacrite and dickite. In the highly significant experiments of Coes (3, 4), in which virtually all the "dense" aluminosilicates and silicates were synthesized, three phases in this system—jadeite, kyanite and sillimanite—were synthesized for the first time. Roy (13) grew andalusite. The problem now, therefore, is to find the conditions of stability of the phases and the effect of temperature, pressure and total composition of a mixture on phase composition and structure. Before discussing phase equilibria, brief comments will be made regarding several of the synthetic minerals.

The albite encountered was in all cases high albite, the same as that found by Tuttle and Bowen (23). It was not examined in any greater detail than to establish that it was not low albite. Analcite is the phase formed with the greatest ease in this system. It is, for all intents and purposes, identical with

natural analcite, as far as optical properties and powder X-ray diffraction data are concerned. Natrolite was not synthesized from any of the compositions used, in the temperature range studied. Natural samples were used to determine a maximum temperature of stability. The synthetic nepheline did not correspond closely to natural nephelines since the latter contain appreciable amounts of potassium. It was, however, identical with synthetic nepheline appearing in the system Na_2O–Al_2O_3–SiO_2. Nepheline Hydrate I is a phase not definitely identified as yet in nature, but one which probably exists. Our data for this phase were very similar to those obtained by Barrer and White (*2*) and their nomenclature was adopted. The powder diffraction data are listed in Table I. Cancrinite was encountered in this study and as hydroxy-cancrinite when no carbonate ions were present. The only apparent distinction from natural specimens was the white color. A phase with the structure of sodalite, as determined from its powder diffraction pattern, was consistently encountered throughout the temperature range used. This is referred to as "hydroxy-sodalite."

STABILITY REGIONS OF THE CRYSTALLINE PHASES

In considering assemblages of minerals as they occur in rocks, conditions of divariant equilibrium are especially applicable. In this state a set of phases exists stably over a certain range of temperature and pressure. For a four component system, four phases will constitute the assemblage (or a smaller number with more degrees of freedom), and the experimental data of particular use to geologists are therefore those which will show what phases may be present at equilibrium in any composition of geologic interest over certain temperature and pressure ranges.

The compositions studied in the system Na_2O–Al_2O_3–SiO_2–H_2O were restricted with respect to both soda and water. As mentioned earlier, only the low soda part of the system—that of most geologic interest—was investigated.

Water contents of mixtures were always such that an aqueous phase was present. (Below the critical temperature in a closed bomb, two aqueous phases, liquid and gas, coexisted.) With three crystalline phases present, therefore, a fourth phase was always a high water liquid or gas. Experimental compositions were confined to those having water as a phase, as the first step in investigating this system. Where there is not excess water over that required by the crystalline structures, reactions are exceedingly slow at the pressures used. Because of this restriction with respect to water, a simplified diagrammatic treatment of the data is possible. The water phase in equilibrium with three crystalline phases may be neglected for purposes of illustration and the compositions of the latter projected on the base of the tetrahedron—the triangle Na_2O–Al_2O_3–SiO_2. For any temperature-pressure range, therefore, a network of triangles results, as shown in Figures 2 to 6. A mixture whose anhydrous composition lies within a certain triangle will under equilibrium conditions at the indicated temperature and pressure be

composed of the three crystalline phases shown at the apices, plus an aqueous solution.

The phase diagrams (Figs. 2 to 6) apply to pressures over the range of about 5,000 to 30,000 psi. Most runs were made at 15,000 psi, a convenient pressure and one at which the reactions studied are reasonably rapid, but runs at other pressures showed that for the range of 5,000 to 30,000 psi, pressure has only a small effect (total spread ~25° C) on temperature of the reactions studied.

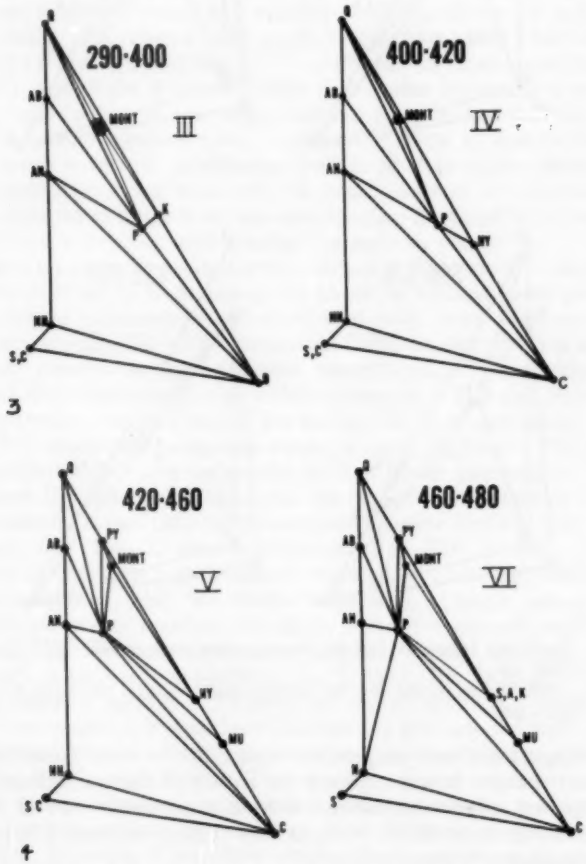
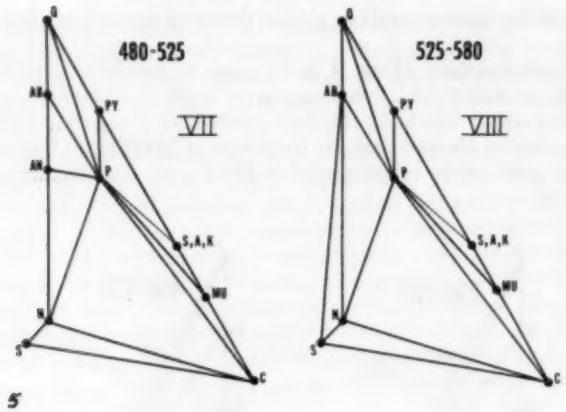


FIG. 3. Stability triangles for the temperature ranges 290–400° C and 400–420° C at 15,000 psi.

FIG. 4. Stability triangles for the temperature ranges 420–460° C and 460–480° C at 15,000 psi.



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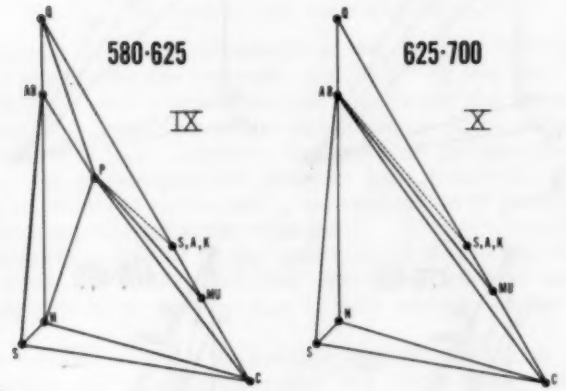

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FIG. 5. Stability triangles for the temperature ranges 480–525° C and 525–580° C at 15,000 psi.

FIG. 6. Stability triangles for the temperature ranges 580–625° C and 625–700° C at 15,000 psi.

The change from one temperature range to the next coincides with a reaction that changes in some respect the nature of the assemblages present. This change will affect compositions only in a particular part of the tetrahedron, and hence most of the triangles may remain unchanged in passing to another temperature range.

The first of the stability triangle diagrams (Fig. 2, I) is a representation of the various four phase assemblages (three crystalline phases plus a water solution) which exist at 250° and pressure of the order of 1,000 atm. Most of the relationships shown probably are valid with little modification to much

lower temperatures. With decreasing temperature other zeolitic phases can be expected to appear. The area shown in black is that within which all compositions yielded only a montmorillonite in the usual runs. The paragonite composition is seen to fall within this area. If these runs made at 250° correctly indicate stability relations, paragonite will not likely form at 250° or lower because a soda montmorillonite is the stable structure at the mica composition. Actually there is a problem with respect to the size and shape of this montmorillonite composition area. The area shown represents approximately the limits of the region in which a mixture is converted to a single phase, montmorillonite, and remains in this condition for a few hours to a few weeks. Experience with much longer runs made since this work was first reported (18), and theoretical considerations of compositional limits suggest that part of the montmorillonite field shown represents a metastable condition, with stable equilibrium requiring a somewhat smaller and irregularly shaped composition area. On grinding albite or analcite in a stainless steel bomb with rods of stainless steel at 250° in water, partial breakdown to montmorillonite occurred. A small amount of montmorillonite would be expected as a result of disproportionation of the albite or analcite on partial solution with more soda entering the aqueous phase.

The next set of stable assemblages is shown in Triangle II. At temperatures above 250° equilibrium among the phases is reached more quickly and hence the stable relationships are established with more certainty. In the temperature range of 250°–290° paragonite forms readily and is a key structure, being present in five different assemblages. The montmorillonite composition field decreases in size with temperature. The size shown is that for a temperature near the top of the range. In the temperature range of II (Fig. 2), quartz and paragonite cannot coexist together stably, although albite, montmorillonite and paragonite form a stable assemblage. At these temperatures the data obtained appear to support the existence of a join analcite-boehmite rather than the paragonite-nepheline hydrate join.

Triangle III (Fig. 3) shows relationships at 290° to 400°. Boehmite is replaced by diaspore, experimentally realized by "seeding" the mixtures. The montmorillonite field has further narrowed. Quartz and paragonite coexist stably alone or together with albite or with montmorillonite. Barrer and White (2) reported synthesizing a phase which they designated as "mordenite" with the composition $Na_2O \cdot Al_2O_3 \cdot 10\ SiO_2 \cdot H_2O$. Natural mordenite contains calcium. If a pure sodium mordenite is a stable phase at these low temperatures, it would not theoretically preclude the stable existence of albite in the presence of water in the same temperature range, but it would render this highly improbable. The question of the stable or metastable nature of authigenic albite, such as that found in marine sediments which have not been heated into the range of these diagrams, is not resolved unequivocally. Mixtures of the albite composition invariably yield analcite first at the lower temperatures, and this converts gradually to albite at temperatures above 290° C indicating the latter as the stable phase. Below this temperature the conversion rate is much lower and it is not easy to decide whether analcite is stable or is failing to convert to albite. In the absence of the

formation of any *stable* assemblage such as analcite + quartz, or analcite + mordenite from the albite composition at low temperatures, we favor the conclusion that albite is a stable phase at lower temperatures in equilibrium with an aqueous solution in this system. To be considered also is the definite predisposition of the gel towards an open zeolite-like network and hence, the easy metastable formation of analcite. Hydroxy-sodalite and hydroxy-cancrinite, although encountered as coexisting phases, were not synthesized on composition. Further studies in this region are needed to resolve the relationship of the feldspathoids to the other mineral phases.

The next change in phase assemblages (Triangle IV) comes upon the decomposition at 400° C of diaspore and kaolinite with the formation of corundum and hydralsite. The latter is a clay phase not reported in nature but found in the study of the system Al_2O_3–SiO_2–H_2O (16).

Triangle V is drawn to illustrate the phase triangles after the appearance of pyrophyllite as a stable phase. With an increase of temperature the primary phase volume within which only montmorillonite crystallizes has shrunk progressively until a "point" composition montmorillonite is stable. This composition approaches that of 1/6 $Na_2O \cdot Al_2O_3 \cdot 4\ SiO_2$ although a very detailed study would have to be made to determine the precise composition of the most stable montmorillonite. The joins pyrophyllite-montmorillonite and paragonite-montmorillonite are of special interest from a structural standpoint. It would be informative to find whether any cases of random interstratification giving rise to mixed-layer effects takes place. In our studies no evidence was found for the formation of such phases even though shorter runs, lower temperatures, and other compositions more suitable for the formation of such phases were tried.*

At the $Na_2O \cdot Al_2O_3 \cdot 2\ SiO_2$ composition, nepheline is not stable in the presence of water in the lower temperature triangles. Below 460° at 1,000 atm., nepheline decomposes to yield nepheline hydrate. In the range of 460–480°, however, nepheline coexists with a water phase, and the relations are as shown in Triangle VI.

In the range 480–525° (Triangle VII) the existence of the join paragonite-nepheline was established experimentally, thus cutting off analcite and the other zeolites from stable co-existence with corundum. The join paragonite-nepheline hydrate was not realized experimentally at the lower temperatures. This triangle, with an upper limit of 525° C, represents relations to the maximum temperature of stability of analcite. Although this temperature agrees reasonably well with that shown by Yoder (25), the variation in this temperature with pressure was found not to be as sharp as he reported (24) (attributed to Morey). The effect of pressure on the equilibrium temperature appears to be slight, amounting to a lowering of about 30° C when the pressure is changed to 1,000 psi from 15,000 psi. Jadeite was not encountered at these pressures, even in runs starting from gels; this was expected from the exhaustive work of Yoder (24).

Triangle VIII depicts stable association from 525° up to decomposition

* In this connection see: Romo and Roy (12), and Mumpton and Roy (11).

temperature of pyrophyllite at 580° C. The dominant position of paragonite is evident. As indicated by the dashed line, it is presumed to exist in stable equilibrium with one or more of sillimanite, andalusite and kyanite. The anhydrous alumino-silicate phase encountered throughout the study was mullite, although in a few runs in this temperature range a phase was obtained which was tentatively identified as andalusite.

Paragonite is the most stable of the layered hydroxy minerals in the system. In the range of water pressures used in this study, it finally decomposes at 625° C (at 15,000 psi). This value was obtained as the maximum temperature of formation in relatively short runs, and might tend to err on the low side due to the tendency for metastable formation of the anhydrous phases near the limit of stability of a hydrate. This possibility can usually be checked against well-crystallized, fairly pure, natural material; but such was not available in this case. The hydroxy-sodalite phase was found to be stable throughout the temperature range. Experiments with synthetic β-Al_2O_3 ($Na_2O \cdot 11\ Al_2O_3$) showed it to be unstable with respect to Al_2O_3 and $NaAlO_2$ (solution) in the presence of water in the range of experiment.

CONCLUSION

From the standpoint of petrology this study probably does more to point up than to solve problems for it serves only as an introduction to the systematic investigation of the quaternary system Na_2O–Al_2O_3–SiO_2–H_2O. Furthermore, the effect on phase relationships of a fifth component, K_2O, is of critical significance, and this awaits future work.

The paragonite-soda montmorillonite relationships were of particular interest in this study. At temperatures above 250° these two structures coexist, and up to 400° they may be joined by either kaolinite or albite as additional members of a stable assemblage in equilibrium with a water phase. At lower temperatures the experiments suggest that a montmorillonite structure will form and persist rather than a mica of paragonite composition. At 250° and lower the condition of stable equilibrium could not be proved for these compositions, however, and possibly paragonite is a stable structure.

Uncertainty also exists with respect to the low temperature stability of albite in this system. The fact that analcite, which forms first on the hydrothermal treatment of albite composition, disappears as albite slowly forms at 290° suggests that albite may be stable in equilibrium with an aqueous solution at much lower temperatures. Unfortunately, reactions among these crystalline phases are extremely slow at low temperatures at the pressure used, and hence the difficulty of establishing equilibrium relationships. In the more complex natural systems, authigenic albite undoubtedly forms at low temperatures.

Temperature limits of stability for crystalline phases in equilibrium with an aqueous phase in this system, at pressures of approximately 1,000 atmospheres (=15,000 psi) may be tabulated as follows: Albite, lower limit probably below 290°; analcite, upper limit 525°, stable at lowest temperatures

and at low pressures; hydroxy-cancrinite, upper limit about 460°; hydroxy-sodalite, stable over temperature range studied (250–700°); Na-montmorillonite, upper limit 480°; natrolite and mordenite, upper limit about 290°; nepheline, lower limit 460°; nepheline hydrate I, upper limit 460°; and paragonite, 250° to 625°.

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STATE COLLEGE, PA.,
Aug. 16, 1956

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APPLICATION OF PUNCHED CARDS TO GEOLOGIC DATA CONCERNING URANIUM DEPOSITS IN SANDSTONE[1]

W. I. FINCH

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ABSTRACT

The punched card has been chosen for use in compiling the great mass of geologic data concerning uranium deposits in sandstone into permanent file. The most valuable uses of the punched-card file are as a multiple index to data and as a means of correlating different data. By using the punched card, uranium deposits in sandstone can also be compared to other metalliferous deposits in sandstone.

Besides the geographic location of the deposit, about 120 different items can be punched on the sides of the card. In the center of the card more detailed data and a summary of the report are given. Although the card is designed for data on a single deposit or group of deposits, topical data on many studies such as chemistry, geobotanical prospecting, and geophysics can be summarized on the card.

INTRODUCTION

Resource studies of various mineral commodities by the U. S. Geological Survey include as one of their main objectives the systematic compilation and synthesis of the vast quantity of published and unpublished geologic information accumulated through the years. So much information has become available on the geology of uranium deposits in sandstone that a manually operated punched card was designed in order to compile and synthesize pertinent data so that broad generalizations and principles could be investigated.

The writer has been greatly aided in the development of the punched-card design described here by E. P. Kaiser, R. E. Melin, L. R. Page, E. M. Shoemaker, and others of the U. S. Geological Survey. This punched-card design is a byproduct of a research project being done by the Uranium Research and Resource Group of the U. S. Geological Survey on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

[1] Publication authorized by the Director, U. S. Geological Survey.

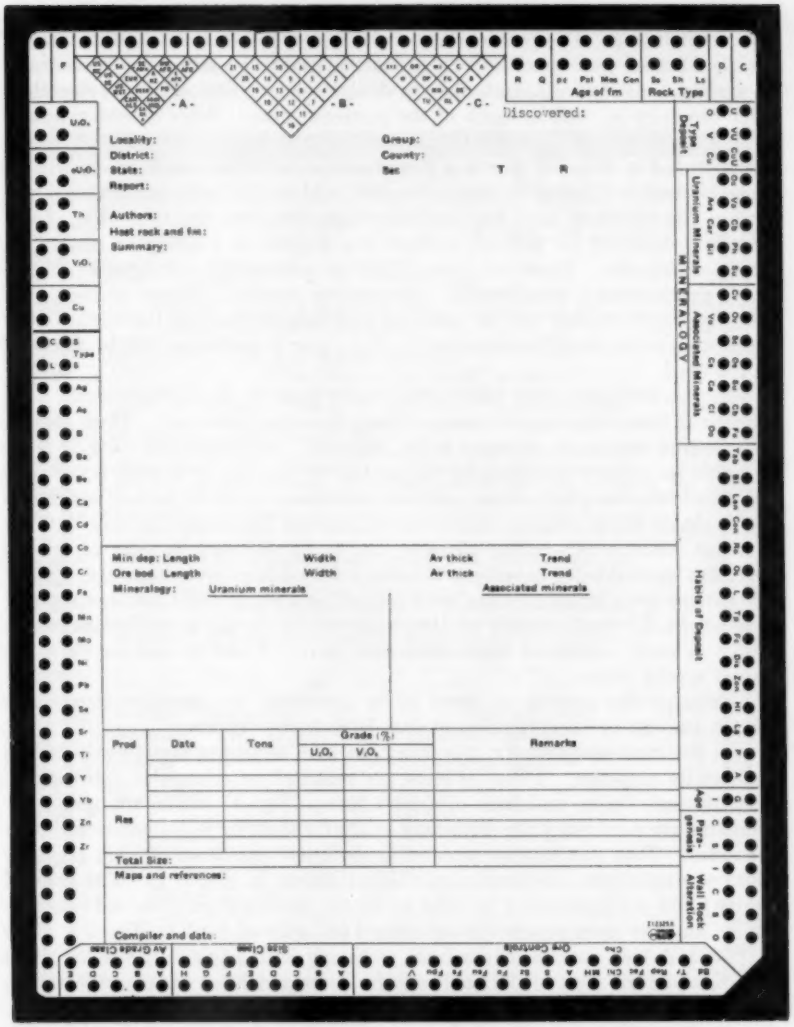


FIG. 1. Photograph of a blank 8″ × 10½″ punched card for uranium in sandstone.

SELECTION, DESIGN, AND MECHANICS OF THE PUNCHED CARD

Uranium geology is outstanding from the viewpoint that never in our history has there been such a bee-hive of activity in geologic studies, exploration, and research on any one commodity as there has been on uranium in the past

8 years. The great number of reports, particularly on uranium in sandstone, is overwhelming. The problem was to find a method of handling this mass of both qualitative and quantitative data so that the items are easily recoverable in various combinations; and, also, to design a file card that would contain a brief summary as well as much of the pertinent data. After consideration of several types of file cards, the manually operated punched card of a type already used in scientific studies (see selected references) was chosen because it can be used to accomplish these objectives and also to serve as a bibliographic card. The punched card for sandstone-type uranium deposits (Fig. 1) is primarily designed for data on a single ore deposit or a group of closely related ore deposits. However, topical data on mineralogy, petrography, chemistry, geochemistry, stratigraphy, gamma-ray studies, isotope studies, and other geologic studies, can be punched and summarized on the card. Data concerning other metalliferous deposits that occur in sandstone can be recorded on the card.

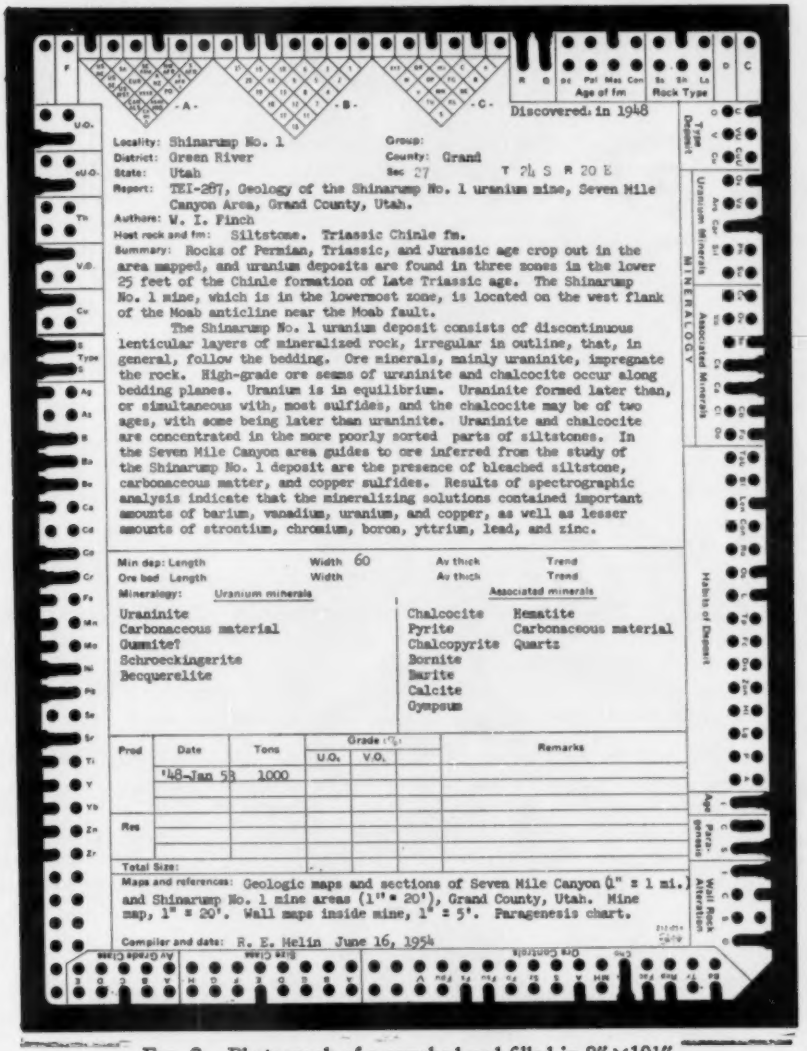
The punched card being used in this study is an 8- by 10½-inch card. The number of items that can be punched along the edge is limited. Thus, a careful selection was made of items to be punched. Although this card is bibliographic in nature, the name of the author or authors of a report and date published have been left off as punched items because of the lack of space and the probable slight use of these items in looking for a card. Only data on chemical analysis of selected elements are to be punched because of limited space but several holes have been left blank for adding more elements. Many other items were considered but were left off because 1) their use was thought to be slight, 2) small number of cases reported, or 3) the lack of room on the card. A small number of blank holes have been left on the card for the addition of special items.

Although the card is designed to be objective, the compiler must do a certain amount of interpretation of data from many reports.

On the card designed for this study, an item is almost always punched to indicate its presence. Items of data are matched to triangular coordinates, lines of single holes, and lines of double holes (Fig. 1). The triangular coordinates are used much the same way as charts showing miles between different cities. Two punches are needed to designate one item of each triangle. Lines of single holes are simply punched as shown in Figure 2. The lines of double holes can be punched in three ways: the shallow punch, the intermediate punch, and the deep punch (lower right-hand side of card in Fig. 2). The shallow and deep punches result from removing with a punch the parts of the card between the edge of the card and the outer and inner holes, respectively. The shallow and deep punches can be observed from the edge of the card. Because a particular hand punch was used to punch the cards as shown in Figure 2, the shallow and deep punches can be differentiated from each other in a stack of cards because the deep punch makes a wider gap than the shallow punch. This is not true of all hand punches or electric punches. The intermediate punch results from removing the portion of card between a pair of holes with a special punch. Thus, from the edge of a card the intermediate punch cannot be seen and is not desirable because visual scanning for an item

of intermediate punch in a stack of cards is impossible. The intermediate punch has been used only sparingly.

The cards can be sorted by threading the cards with a long (knitting) needle through the hole opposite the desired item, cards that are punched for



Discovered: in 1948

Locality: Shinarump No. 1 Group:
District: Green River County: Grand
State: Utah Sec 27 T 24 S R 20 E
Report: TEI-267, Geology of the Shinarump No. 1 uranium mine, Seven Mile Canyon Area, Grand County, Utah.
Authors: W. I. Finch
Host rock and fm: Siltstone. Triassic Chinle fm.

Summary: Rocks of Permian, Triassic, and Jurassic age crop out in the area mapped, and uranium deposits are found in three zones in the lower 25 feet of the Chinle formation of Late Triassic age. The Shinarump No. 1 mine, which is in the lowermost zone, is located on the west flank of the Moab anticline near the Moab fault.

The Shinarump No. 1 uranium deposit consists of discontinuous lenticular layers of mineralized rock, irregular in outline, that, in general, follow the bedding. Ore minerals, mainly uraninite, impregnate the rock. High-grade ore seams of uraninite and chalcocite occur along bedding planes. Uranium is in equilibrium. Uraninite formed later than, or simultaneous with, most sulfides, and the chalcocite may be of two ages, with some being later than uraninite. Uraninite and chalcocite are concentrated in the more poorly sorted parts of siltstones. In the Seven Mile Canyon area guides to ore inferred from the study of the Shinarump No. 1 deposit are the presence of bleached siltstone, carbonaceous matter, and copper sulfides. Results of spectrographic analysis indicate that the mineralizing solutions contained important amounts of barium, vanadium, uranium, and copper, as well as lesser amounts of strontium, chromium, boron, yttrium, lead, and zinc.

Min dep: Length Width 60 Av thick Trend
Ore bod Length Width Av thick Trend

Mineralogy:

Uranium minerals: Uraninite; Carbonaceous material; Gummite?; Schroeckingerite; Becquerelite

Associated minerals: Chalcocite, Pyrite, Chalcopyrite, Bornite, Barite, Calcite, Gympsum, Hematite, Carbonaceous material, Quartz

Prod	Date	Tons	Grade (%) U$_3$O$_8$	Grade (%) V$_2$O$_5$	Remarks
	'48-Jan 53	1000			
Res					

Total Size:

Maps and references: Geologic maps and sections of Seven Mile Canyon (1" = 1 mi.) and Shinarump No. 1 mine areas (1" = 20'), Grand County, Utah. Mine map, 1" = 20'. Wall maps inside mine, 1" = 5'. Paragenesis chart.

Compiler and date: R. E. Helin June 16, 1954

FIG. 2. Photograph of a punched and filled-in 8" ×10½" punched card for uranium in sandstone.

this item will drop out. Intermediate punched cards will drop about one-quarter of an inch below the unpunched cards and with another needle these partially dropped cards may be threaded and removed from the rest. For faster and routine sorting one may wish to use several needles or patented devices. In practice, scanning the edges of large numbers of cards for a punched item often eliminates many cards to sort by the use of a needle. Because the cards are not filed in any given order, refiling is not necessary.

USES OF THE PUNCHED CARD

The punched card described in this report has many uses, and new ones become apparent as more cards are filled out. The value of the card as a multiple index to data and as a means of correlating various groups of data cannot be over-emphasized.

As a bibliographic card, the punched card serves as a permanent resource file on published and unpublished reports. The multiple index is an invaluable tool in searching for data on specific items. Answers to questions such as the following can be sought:

1. What data are available about uranium deposits in sandstone in India or some other country or area?
2. What data are available about the geochemistry of vanadium?
3. What localities have a reported occurrence of torbernite, or some other mineral?
4. Where are the uranium deposits in sandstone that contain asphalt-like substances?
5. Where are the uranium deposits in sandstone that contain significant amounts of cobalt or some other element?

Correlation studies can be made easily using the punched card. Important common denominators can be sought between certain groups of geologic data for uranium, vanadium, copper, mercury, manganese, and other metalliferous deposits occurring in sandstone in different areas and geologic environments. Some of the more important questions that can be answered are as follows:

1. What is the distribution of the different size and grade classes of deposits or of the deposits in different areas or different age groups of formations, or of different types or habits of deposits?
2. What percent of the different types of deposits are oxidized? Unoxidized?
3. What elements (listed on the left-hand side of the card) are diagnostic of the large size classes? In different areas?

An important use of the punched card is to compile resources of uranium in sandstone for the world, United States, and smaller areas. Although much of the data may be out-of-date or of different caliber, orders of magnitude can be made of the resources. One use that has become apparent after reviewing

many reports is that the punched card is a good check list for the completeness of reports. A quick check by the author, supervisor, or critic will reveal the inadequacies of a report on uranium deposits in sandstone.

Another use of this card is to compile, file, and analyze field notes.

U. S. GEOLOGICAL SURVEY,
DENVER, COLO.,
Aug. 10, 1956

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APPENDIX

Key to punched card for uranium deposits in sandstone

Edges of the Punched Card

Top edge:

Foreign (F)

Punch only for foreign.

Major area (A), state or country (B), and county (C)

This is a two-punch co-ordinate system with a triangle for major areas (A), for states and countries (B), and for provinces or counties (C). The major area (triangle A) is punched as follows: example, India—use diamond marked ASMI-IND and punch second hole from the left and the last hole. Similarly, each state or country (triangle B) is punched by the code number as given in the following lists. The code number for India is 4. The county or other subdivision (triangle C) is punched according to its initial letter.

NORTHEASTERN U. S. (US, NE)

1. Connecticut
2. Illinois
3. Indiana
4. Iowa
5. Maine
6. Massachusetts
7. Michigan
8. Minnesota
9. New Hampshire
10. New Jersey
11. New York
12. Ohio
13. Pennsylvania
14. Rhode Island
15. Vermont
16. Wisconsin

SOUTHEAST U. S. (US, SE)

1. Alabama
2. Arkansas
3. Delaware
4. Florida
5. Georgia
6. Kentucky
7. Louisiana
8. Maryland
9. Mississippi
10. Missouri
11. North Carolina
12. South Carolina
13. Tennessee
14. Virginia
15. West Virginia

WESTERN U. S. (US, WST)

1. Arizona
2. California
3. Colorado
4. Idaho
5. Kansas
6. Montana
7. Nebraska
8. Nevada
9. New Mexico
10. North Dakota
11. Oklahoma
12. Oregon
13. South Dakota
14. Texas
15. Utah
16. Washington
17. Wyoming

CANADA–ALASKA (CAN, ALS)

1. Alberta
2. British Columbia
3. Labrador
4. Manitoba
5. Maritime Provinces
5. New Brunswick
5. Newfoundland
6. Northwest Territories
5. Nova Scotia
7. Ontario
5. Prince Edward Island
8. Quebec
9. Saskatchewan
10. Yukon
11. Greenland
12. Iceland
13. Alaska

CENTRAL AMERICA WEST INDIES ATLANTIC OCEAN (CA, WI, A)

1. Bahamas
2. British Honduras
3. Costa Rica
4. Cuba
5. Dominican Republic
6. Guatemala
5. Haiti
7. Honduras
8. Jamaica
9. Lesser Antilles
10. Mexico
11. Nicaragua
12. Panama
13. Puerto Rico
14. San Salvador
13. Virgin Islands
15. North Atlantic islands and bottom rocks
16. South Atlantic islands and bottom rocks

SOUTH AMERICA AND ANTARCTICA (SA)

1. Argentina
2. Bolivia
3. Brazil
4. British Guiana
5. Chile
6. Colombia
7. Surinam (Dutch Guiana)
8. Ecuador
9. French Guiana
10. Paraguay
11. Peru
12. Uruguay
13. Venezuela
14. Antarctica

EUROPE (EUR)

1. Albania
2. Austria
3. Benelux
4. Bulgaria
5. Czechoslovakia
6. Denmark
6. Finland
7. France
8. Germany
9. Great Britain
10. Greece
11. Hungary
12. Italy
9. Ireland
6. Norway
13. Poland
14. Portugal
15. Rumania
16. Spain
17. Switzerland
6. Sweden
18. Yugoslavia
19. Mediterranean Sea

UNION OF SOVIET SOCIALIST REPUBLICS (USSR)

1. Armenia
2. Azerbaijan
3. Estonia
4. Georgia
5. Karelia
6. Kazakh
7. Kirghiz
8. Latvia
9. Lithuania
10. Moldavia
11. RSFSR*
12. Tadzhik
13. Turkmen
14. Ukraine
15. Uzbek
16. White Russia

ASIA MINOR AND INDIA (ASMI, IND)

1. Aden
2. Afghanistan
3. Cyprus
4. India
5. Iran
6. Iraq
7. Israel
8. Jordan
9. Kuwait
10. Lebanon
11. Oman
12. East Pakistan
13. West Pakistan
14. Saudi Arabia
15. Syria
16. Turkey
17. Yemen

SOUTHEAST ASIA (SE, ASIA)

1. Bhutan
2. British Borneo
3. Burma
4. Ceylon
5. China
6. Indochina
7. Indonesia
8. Japan
9. Korea
10. Malaya
11. Nepal
12. Philippine Republic
13. Thailand (Siam)

AUSTRALIA–NEW ZEALAND (A, NZ)

1. Bismarck Archipelago
2. New Caledonia
3. New Guinea
4. New Hebrides
5. New South Wales
6. New Zealand
7. Northern Territory
8. Queensland
9. Solomon Islands
10. South Australia
11. Tasmania
12. Victoria
13. Western Australia

PACIFIC OCEAN ISLANDS AND BOTTOM ROCKS (PO)

1. To be numbered when used

NORTHWEST AFRICA (NW, AFR)

1. Algeria
2. French Equatorial Africa
3. French Morocco
4. French West Africa
5. Gambia
6. Gold Coast
7. Liberia
8. Libya
9. Nigeria
10. Portuguese Guinea
11. Rio de Oro
12. Sierra Leone
13. Spanish Guinea
14. Spanish Morocco
14. Tangier

* Russian Soviet Federated Socialist Republic.

EAST AFRICA–INDIAN OCEAN (E AFR, I)

1. Abyssinia
2. Anglo-Egyptian Sudan
3. British Somaliland
4. Egypt
5. Eritrea
6. French Somaliland
7. Italian Somaliland
8. Kenya
9. Madagascar
2. Sudan
10. Tanganyika
11. Uganda
12. Zanzibar
13. Indian Ocean

SOUTHERN AFRICA (S AFR)

1. Angola
2. Basutoland
3. Bechuanaland
4. Belgian Congo
5. Mozambique
6. Northern Rhodesia
7. Nyasaland
8. Southwest Africa
9. Southern Rhodesia
10. Swaziland
11. Union of South Africa

Report type (R)

Topical report—examples—geobotanical prospecting, chemistry.....NP[1]
Topical reports can be coded and punched according to age of formation, rock type, mineralogy, element, etc. or for reports that do not fall into such classifications—holes can be assigned for the special topics

General report of area, district, or group.....SP[2]
Report or card for a *single* deposit.....DP[3]

Quality of data (Q)

Monthly, semi-annual or annual report.....NP
Normal study.....SP
Reconnaissance study.....IP[4]
Detailed—long term—study.....DP

Age of host formation

Precambrian (pC)

Huronian or older.....SP
Younger than Huronian.....DP

Paleozoic (Pal)

Cambrian, Ordovician, Silurian, or Devonian.....SP
Carboniferous or Permian.....DP

Mesozoic (Mes)

Triassic.....SP
Jurassic or Cretaceous.....DP

Cenozoic (Cen)

Paleocene or Eocene.....SP
Oligocene, Miocene, Pliocene, or Pleistocene.....DP

Rock types—sedimentary or the metamorphic equivalents. If major constituent use shallow punch and if minor constituent use deep punch.

Sandstone, conglomerate or arkose (Ss)
Shale (include mudstone, siltstone, tuff) (Sh)
Limestone (Ls)

D—hole is not punched—use for alinement of cards.
C—Classification of report
Unclassified—NP
Classified—SP

---

[1] No punch.
[2] Shallow punch.
[3] Deep punch.
[4] Intermediate punch—punch out between holes.

Right edge:

Type deposit: based on production or assay data, deposits are typed by major ore metal content, major metal named first. Uranium is used here as U_3O_8 and vanadium is used as V_2O_5.

Uranium (U) ..... SP
Other, i.e., Au-U, Pb-U, Hg, etc. (O) ..... DP
Vanadium-Uranium (VU) ..... SP
Vanadium (V) ..... DP
Copper-Uranium (CuU) ..... SP
Copper (Cu) ..... DP

Mineralogy

Note: Shallow punch for outer row of mineral groups, intermediate punch for inner row of mineral groups, and deep punch where both groups are present. Groups arranged to eliminate intermediate punch as much as possible.

Uranium minerals[5]

Oxides (Ox)
Vanadates (Va)
Arsenates (Ars)
Radioactive carbonaceous material (Cb)
Carbonates (Car)
Phosphates (Ph)
Silicates (Sil)
Sulfates (Su)
Others (IP under Su)

Associated minerals—common rock forming minerals generally excluded

Copper vanadates (Cv)—volborthite and calciovolborthite
Absence of carbonaceous material (intermediate punch under Cv)
Other vanadates (Ov)
Vanadium oxides and hydrous oxides (Vo)
Secondary copper (Sc)
Other sulfides (Os)
Copper sulfides, include chalcopyrite (Cs)
Sulfates (Su)
Carbonates (Ca)
Non-radioactive carbonaceous material (Cb)
Clay—bentonite, etc. (Cl)
Iron oxides (Fo)
Oxides other than Fe and V (Oo)
Others (IP under Sc)

Habits of deposit

Tabular (Tab)
Blanket (Bl)
Lenticular, in cross-section (Len)
Concretionary (Con)
Rolls (Ro)
Ore shoots (Os)
Logs-replacement (L)
Trash pockets (Tp)
Fracture coatings (Fc)
Disseminated (ore minerals) (Dis)
Zoning of U, V, Cu, Fe, or lime (Zon)
High lime (more than 6 percent) as carbonate (Hl)
Low grade halo (Lg)
Placer ore minerals (P)
Asphaltic, lignitic or petroliferous (A)

Age of mineralization (type of determination) indicate time of mineralization in summary

Geologic (G) ..... SP
Isotopic (I) ..... DP

Paragenesis of uranium minerals

Relation of primary uranium minerals to:

Cementation (C)

Earlier than cement ..... SP
Later than cement ..... IP
Contemporaneous or both ..... DP

[5] See Weeks, A. D., and Thompson, M. E., 1954, Identification and occurrence of uranium and vanadium minerals from the Colorado Plateau: U. S. Geol. Survey Bull. 1009-B.

Sulfides (S)
Earlier than sulfides.....SP
Later than sulfides.....IP
Contemporaneous or both.....DP

Wall rock alteration

Alteration of mudstone, siltstone, and sandstone

Intensity (I)
None.....SP
Present.....DP

Color (C)
Gray or green.....SP
Brown or yellow.....IP
Different colors.....DP

Silicification (S)
Absent.....SP
Present.....DP

Oxidation (O)
Present.....SP
Mostly absent.....DP

Bottom edge:

Ore controls—in part, guides to ore and in part, evidence that may be the cause of localization of ore minerals. Use shallow punch except where noted; holes in second row retained for additions.

Sedimentary

Bedding—higher concentration of ore minerals along and parallel to beds (Bd)
Traps—caused by small scale features such as blocks or beds or mudstone or clay (Tr)
Replacement—of wood, clay, chert, qtz., etc. (Rep)
Facies change or pinchouts—local or regional (Fac)
Channel or lense control
Deposit inside channel (Chi).....SP
Deposit outside channel (Cho).....DP

Structural

Deposit located on monocline or homocline (MH)
Deposit located on anticline (A)
Deposit located in syncline (S)
Deposit located in shear or brecciated zone (Sz)
Coincidence of thick or high grade ore on or in fractures or joints (Fo)
Minerals contained in fractures:
Oxidized uranium minerals (Fsu)
Sulfides (Fs)
Unoxidized uranium minerals (Fpu)
Vein deposit (V)

Size class: Sum of production, and indicated and inferred reserves.

A	0.9 ton (short) or less	E	1,000–9,999 tons
B	1–9.9 tons	F	10,000–99,999 tons
C	10–99.9 tons	G	100,000–999,999 tons
D	100–999.9 tons	H	1,000,000 tons or more

Average grade class

A 0.005–0.0099 percent U_3O_8
B 0.010–0.099 percent U_3O_8
C 0.100–0.499 percent U_3O_8
D 0.500–0.999 percent U_3O_8
E 1.00 percent or more U_3O_8

Left edge:

Assay data:

U_3O_8, equivalent (e) U_3O_8, and Th each have a block of 4 holes to indicate ranges of assays: (To convert U to U_3O_8, multiply value of U by 1.18)

Upper left-hand hole—less than 0.010 percent.....SP
Upper right-hand hole—0.010 to 0.049 percent.....DP
Lower left-hand hole—0.050 to 0.099 percent.....SP
Lower right-hand hole—0.100 percent or more.....DP

Cu and V_2O_5 each have a block of 4 holes to indicate grade ranges

Upper left-hand hole—less than 0.10 percent.....SP
Upper right-hand hole—0.10 to 0.49 percent.....DP
Lower left-hand hole—0.50 to 0.99 percent.....SP
Lower right-hand hole—1.00 percent or more.....DP

Selected elements:

Each element has been assigned a value (shown below) obtained by multiplying the geometric mean of barren sedimentary (sandstone) by a factor of 10 (roughly 2 standard deviations from the mean). The objective here is to indicate in statistical manner whether or not the sample (rock) has been mineralized with a particular element. The geometric means used are ones for barren sandstone from the Colorado Plateau as determined by Shoemaker, E. M., Newman, W. L., and Meisch, A. of the Geological Survey, except where noted. From a report, a card is made for mean values if given, otherwise for the highest value.

Type of analysis

Chemical (C).....SP
Spectrographic or X-ray (S).....DP
Mineralogic.....NP

Type of sample

Representative sample—mill pulp, composite of channel samples (L).....SP
Unrepresentative sample, grab, single channel, chip, cone (S).....DP

Elements: a shallow punch is made for value below the cutoff and a deep punch for a value equal to or above the cutoff

Ag	0.0001 percent (about 3 ounces/ton)	Mo	0.010[7] percent
As	0.01 percent	Ni	0.005 percent
B	0.02 percent	Pb	0.010 percent
Ba	0.02 percent	Se	0.005[7] percent
Be	0[6] percent	Sr	0.025 percent
Ca	5.00 percent	Ti	0.600 percent
Cd	0.05 percent	Y	0.010 percent
Co	0.005[7] percent	Yb	0.005 percent
Cr	0.005 percent	Zn	0.050[7] percent
Fe	5.000 percent	Zr	0.075 percent
Mn	0.150 percent	Four	pair of holes for additional elements

In cases where chemical or spectrographic analysis are not reported, the elements Ag, As, Ba, Cd, Co, Cr, Mo, Ni, Pb, Se, Sr, Ti, Y, Yb, Zn, and Zr, contained in the formula for minerals reported, are indicated by a shallow punch.

Center of Card

Most of the entries to be made in the center of the card are self-explanatory. The main purpose of the center of the card is to provide detailed data that are punched as a general category as well as adding new information. The blanks that need clarification are discussed below.

Locality—use only name of deposit, section number or some identifying label.

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[6] Rankama, Kalervo, and Sahama, Th. G., Geochemistry: Chicago, 1950 Table 5.52, page 226.
[7] Estimated by E. M. Shoemaker.

Summary: (continue on back of card if necessary) Include all pertinent facts, in a brief form, particularly data presented as groups, numbers, etc., that are punched only in general terms.

The form suggested is as follows:

1. General geology
   - A. Stratigraphy—other than above, thickness, sedimentary structures
   - B. Structure and igneous rocks.
2. Habits of deposit—shape, texture of ore, paragenesis, etc.
3. List of analysis of samples (summarize)—general location
4. Guides to ore
5. Mine workings
6. Origin of deposit, results of age determinations

Mineralogy

Associated minerals—omit common rock forming minerals unless diagnostic.

Production

Remarks—owner, lessee, or shipper, mill shipped to.
Total size—sum of production and reserves and average grade of production and reserves.
Maps and references—types and scales of maps, areas covered.

DISCUSSIONS

DISCUSSION OF URANO–ORGANIC ORES

Sir: The contributed discussion on uranium-bearing mixtures variously referred to as "urano-organic ores," thucholite or uraniferous hydrocarbons now approximates a paraphrase of Aesop's fable concerning the seven blind men who went to see an elephant. Not being wise enough to be blinded by my wisdom, I would like to call attention to some aspects of the natural occurrence of this elephant-sized atom, to set aright some misstatements concerning my own concept of Colorado Plateau uranium ores and to itemize some unvarying associations of the so-called combustible ores of uranium. Generally knowledge would be improved by treating the entire subject inductively and leaving deduction with all its "ifs" and "buts" to verbal discussion.

Davidson (4) intimates that "so-called wood trash has in many instances formed the focus of rich uranium mineralization." Actually I know of no woody carbon which has significant uranium mineralization; in my experience the only logs or "trash" with uranium had been replaced previously by carbonates or by vanadium minerals and pseudomorphs of this premineralization are common in Morrison ores at Chilchinbeto, Egnar, Slick Rock and the Henry Mts. Some so-called logs in the Shinarump conglomerate at Monument No. 2 Mine are tubular replacements of conglomerate still containing abundant calcite and vanadates and the uranium is precipitated from solution by the latter mineral substances. This premineralization is an important feature where the "hydrocarbons" are a minor element in the deposit; this premineralization has been studied most by Waters (8, p. 38–45) but all petrologists have noted it. Hydrocarbon nodules in the San Rafael Swell represent a very different mineralization and were described very early (1, p. 29) as follows:

> The jasperoid replacements take a variety of forms which are hard to identify with any control or guidance. Replacements with cavity forms penetrate from the pebble border. . . . The "dental cavity" type of replacement usually has a mammillary outer form that is indistinguishable in loosened pieces from the nodules out of clay. . . . The jasperoid carries uranium in its own right and in much greater *aggregate* amount than the hydrocarbon so that the hydrocarbon must act either as an accumulator or have its own stock of uranium to reach its higher per cent content. The nodules in clay have all the variety known for concretions. Some cross-cut the clay lamination and others displace the lamination laterally. . . .
>
> These nodules are enigmatical. Like the dental cavity type of hydrocarbon, some mineral was removed to provide space and some ionized solution was essential. The hydrocarbon or hydrocarbon components were in most instances merely fellow migrants with this ionized solution. . . . The accumulation of uranium by hydrocarbon seems to be discontinuous with at least two main stages,

represented by the difference in uranium content for the two physical types of hydrocarbon.

This should leave no doubt about my view that uranium deposition at its present site was from solution rather than by mechanical procedures and anyone who will go through the data in the above report will find a more quantitative analysis of uranium and hydrocarbon distribution in the ore than is given by Kerr and Kelley (5). Furthermore this hydrocarbon takes a place in the mineralization sequence that matches Waters premineralization phase.

The source for the uranium of the solution which reacted with the jasperoid is the real problem in deciphering the history of the Plateau ores. The magmaticist adherents plead oracular immunity when they attribute uranium to magmatic agencies; seemingly this absolves them from identifying passage of uranium solutions out of an igneous or a transformed rock source body or even of producing the corpus delicti of the magma. Actually calling upon an omnipotent magma is no answer to Plateau problems; magmas or even transformed rocks can give off only those elements which they had or had acquired and, which are not required to form a part of the ultimate igneous or transformed mass. A logical magmaticist should consider that it is essential, first, to show that a magma-type rock body exists, and second, to demonstrate by some pattern or component that it supplied the uranium. The magmaticists have shown only existence of solutions, which every recent report considers essential to present distribution of uranium. Where did the solutions acquire the uranium? Why did they leave over 90 per cent of it either above the mid-Triassic unconformity or in the middle part of the Morrison Formation?

Three items concerning distribution of uranium are outstanding. First, over ninety percent of all uranium deposits are in or immediately adjacent to known "shoestring" sandstone and conglomerate sediments representing old river deposits; exceptions are the limestone occurrences. Second, all the productive river deposits have red jasperoid pebbles containing "Word stage" fossils (2, p. 19); uranium content is proportional to the red pebble density although a lesser density relative to uranium content of the channel is found in eastern Morrison deposits and western Shinarump deposits. Third, productivity comes from the most impermeable Shinarump conglomerates (+25 percent is −325 mesh detritus) and abundant mudstone facies of the Morrison formation; permeable facies are leached of their uranium; impermeability and reduced mobility to solutions is more important to uranium content than mobility, which is considered to be the all-important requirement for hypogene mineralization. Every major item in the pattern to uranium occurrence that would expedite discovery is related to a sedimentary river channel feature; to this geologist, a concept of origin that promotes discovery seems the more probable. The uranium enrichment sites along channels are at structural interruptions to these sedimentary features. (2, p. 21; 3, p. 43.)

The river channel pattern feature, which is repeated on the Witwatersrand and at Blind River, incited me to attempt to locate a plausible source of uranium for the solutions. The ubiquitous red jasperoid pebbles found in all "shoestrings" accompanying all Plateau uranium deposits in the Morrison

and Shinarump strata were studied in some detail; the jasperoids with highest uranium content came from the Dirty Devil deposits on the San Rafael Swell (1, p. 22) but all red jasperoid pebbles carry some uranium even when finely pulverized and separated from their introduced hydrocarbon and vanadates.

The pebbles have fusiline, brachiopod, and bryozoa fossils, which suggest an age in the upper Leonard Series or Word Series. In the northern and eastern edge of the Plateau, strata of this age include the Park City and Phosphoria Formation which are uranium bearing. In the southern edge of the Plateau they include the upper Kaibab limestone and shaly limestone equivalents of the Cloud Chief gypsum, which are also uraniferous. Also, a uraniferous stratum was intersected deep in an exploration oil well south of the San Juan River on Hoskinini Mesa. The uraniferous Shinarump channels originate in areas where these weakly uraniferous bearing formations were being denuded during the upper Triassic (2, p. 12). Thus the Plateau uranium occurrences, particularly at the Shinarump horizon, are related to a special sedimentary structure, significant uranium is identified with a special pebble type, which in turn is derived from known uraniferous strata. This asks for no oracular immunity.

Age of the ores has been said to support hydrothermal origin. Actually this age for the ore was brought out before the hydrothermal origin ever came up (1, p. 32) and is accounted for on a basis entirely unrelated to magmatic origin.

The combustible ores of uranium, which are insoluble or only feebly soluble in organic compounds, are really a world type and everywhere they give evidence of having moved along with ionized solutions. I have the piece of Kimberley Reef in which uranium was discovered in productive amounts on the Witwatersrand; this phenomenal specimen has about 8 per cent of U_3O_8 and the rims of pebbles are indented deeply by the pellet-like hydrocarbons. Uranium in this conglomerate and in all hydrocarbon occurrences is extremely mobile; wherever groundwater moves along the Rand reefs, and evaporates on the haulageways of the mines, encrustations of yellowish green uranium sulphate mark the high grade sections. Mobility of uranium in this deposit, and partial segregation from its daughter elements, makes any great age unusual.

The kolm from the upper Cambrian age alum shales of Sweden is another instance of combustible ore where extremely large nodules have up to 0.5 percent U_3O_8 or an accumulation 20 times as rich as that in the shale itself. Much kolm is in displacement concretions. However, the west wall of the Gullhagen quarry has many replacement concretions with some relic banding of the shale bedding planes crossed by the hydrocarbon shells as in the shale at Dirty Devil No. 2 occurrence on the San Rafael Swell. The vanadium-rich fissure fillings of hydrocarbon at Stora Stolan in Sweden have almost undetectable uranium. Repeated cases show that "urano organic" substance occurs only where inorganic substances have been dissolved and this presumes activity of ionized solutions.

The increasing listings of occurrence for "urano-organic" substances only serves to multiply the cases of final emplacement by ionized solutions. Assign-

ment of the Kolm in the alum shales to a magmatic origin would make it the most "tele" of telethermal deposits, yet those physical properties that I have measured correspond closely to those in the San Rafael hydrocarbons. The kolm and its uranium is not at its original site but I believe its uranium originated in the shale deposits. Ramdohr (7) and Liebenberg (6) have demonstrated to me, at Heidelberg and Johannesburg, their evidence for detrital origin of uranium in the Witwatersrand; generally much of the data is suggestive but inconclusive; however, both authors have one specimen where the uraninite form cannot be explained other than by abrasion. Apart from pattern, age, and every other feature, those two specimens proclaim some detrital origin. Over 90 percent of the uranium has moved around but that is a subject which has been discussed elsewhere at the request of Liebenberg.

The general opinion, including my own, if Kerr and Kelley will permit me to correct their statement of my ideas, is that the "elephant" of the Colorado Plateau is at least 90 percent solution made. Specimen amounts of uranium occur in all strata, but when production is assessed, over 90 percent comes from river deposits of Shinarump conglomerate just above the mid-Triassic unconformity and from the vicinity of river deposits of the Morrison Formation; both the impermeable Chinle shales and the very permeable sandstones above lack even traces of uranium except on fracture surfaces. The reaction effect of the solutions on the silicate host rocks to ore bodies indicates alkalinity and some warmth but not above that measured for deep artesian circulations; the solutions were hydrothermal. But no evidence exists that the solutions in any of the great uranium districts are hypogene, and this is essential to establish a magmatic origin; hydrothermal and hypogene are not synonymous. The Moenkopi red beds are unaffected in the San Rafael Swell, Circle Cliffs, Monument Valley and White Canyon regions; they have some peculiar features in the Colorado Canyon above Moab but no ore is known within eight miles. The strata, from the bottom of the Wingate sandstone to the top of the Entrada, show no evidence of solution penetration where Morrison deposits occur in the Uravan, Egnar-Slick Rock, Lukachukai areas; changes which appear in the Carrizos and Henry Mts. are related to stocks and volcanic necks and not to ores.

Considered from all points of view the evidence bearing upon emplacement of the uranium indicates that the Plateau ores owe their present position to solutions that were mildly hydrothermal but not hypogene.

GEORGE W. BAIN

AMHERST COLLEGE,
AMHERST, MASS.,
Aug. 10, 1956

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SULFUR ISOTOPE ABUNDANCES IN SULFIDE MINERALS

Sir: The paper by Kulp, Ault, and Feely (1) on abundance of the isotopes of sulphur in sulphide minerals presents some extremely interesting data and, like earlier papers by Thode and his associates, calls attention to a new tool that is capable of important contributions to the understanding of ore genesis.

Just to recall the thesis: The ratio of S^{32} to S^{34} in meteorites has been found to be always between 22.20 and 22.24, which is assumed on grounds of logic rather than on direct evidence to have been the ratio in the primeval earth and to be the ratio still existing in the mantle underlying the crust. Any departures from this ratio are the result of partial separation of the two isotopes and reflect the geologic history of the resulting sulphides.

The authors, in addition to presenting the results of many isotopic analyses, offer theories as to their implications and these theories are most welcome. Nevertheless, it is within the province of geologists, even those relatively uninitiated in the techniques, to measure the theories against what is known or believed about the origin of sulphides.

In fact, even the authors seem at times to fall back on geological prejudices rather than following through what might seem the logical consequences of their results. Thus, the fact that "magmatic" sulphides (with certain exceptions) have a uniform ratio lying within the meteoritic range is taken as evidence that the enclosing mafic or ultramafic rock was (or at least "may have been") derived from the mantle. But when it comes to sulphides from Central New Mexico, which likewise have a quite uniform ratio and likewise fall within the meteoritic range, they seem unwilling to admit that the sulphur could have come from the mantle. They say (p. 143): "Since there is no obvious reason for believing that the mineralizing solutions . . were directly derived from the mantle it seems likely that they were derived from a reasonably homogeneous source within the crust which contained an average content of sulfur isotopes."

Would it not seem equally logical to say: "Since there is no obvious reason for believing that the mineralizing solutions were *not* derived from the mantle it seems likely that they came from magma or solutions that rose from a deep source"? Not to the authors. They conclude, in effect, that any sulphur having an isotopic ratio within the meteoritic range either was or was not derived from the mantle, according to taste. This may be true, but if so we can draw no positive conclusions about even magmatic sulphides.

Some of the most intriguing results and apparent anomalies are in samples

from the Mississippi Valley region. Of six samples from the Joplin district, two lie within the meteoritic range and four lie above it. On the other hand, samples from the Illinois-Iowa-Wisconsin district all fall below this range (averaging 22.06). Samples from Southeast Missouri have virtually the same average (22.05) and also lie below the meteoritic range with the exception of one (22.40) that a sampler would call a "high erratic" from "St. Joseph" (not a very definite locality!). Is there a significant difference between the Joplin region and the rest of the Mississippi Valley or is the difference only apparent due to the really rather small number of samples from such a vast region?

The study of galena from Ivigtut, Greenland, is a bit disconcerting as lead from this source was formerly considered "the closest approach to primeval lead" (2). However, the sulphur isotope ratio of the galena turns out to be distinctly lower (21.53) than that of meteoric sulphur, indicating, according to the authors, a source in metasedimentary rocks rich in sulphate. Considering the geology of the occurrence, this is about the last place one would look for sulphur of sedimentary origin. The authors consider that the lead was also not derived from the mantle because its isotopic composition does not agree with that of an olivine bomb from an (sic) Hawaiian flow. Without disputing the conclusion, one may opine that a lone bomb is a rather meager sampling of the entire mantle of the earth!

The reasons for variation in isotopic ratios might be clearer if we knew more about fractionation. Most of the authors' suggestions depend on a single mechanism, namely, oxidation-reduction at the surface. Evidently this is a process that has definitely been shown to be effective but does it follow that this is the only one among all geological processes that is capable of partial separation of S^{32} from S^{34}? If, for example, fractionation can occur through separation of a gas from a liquid phase anywhere in the complex history of ore deposition we need not resort to sedimentation as the explanation of everything. I am not competent to say that such an alternative is or is not possible, but it does seem much too early in the new game to rule out all modes of fractionation other than sedimentary.

It is quite natural that in the exploratory stage of investigation any readily available sulphides were tested, some of them from definitely designated localities and others of vague or unknown origin. But now that significant differences in isotopic ratios have been shown to exist it will be highly desirable if the care and precision devoted to collecting the samples be commensurate with the time and cost of the laboratory work, which is by no means trifling. For example, specimens from the Illinois-Iowa-Wisconsin district show relatively wide variation but to speculate on its significance is idle without knowing not only what mine the specimens came from, but precisely what part of what orebody, with an accurate description of their mineralogical association and geological occurrence. No doubt the authors are well aware of this consideration, but in view of the long time that elapsed before petrologists became alert to the importance of sampling as a prelude to chemical analyses, the plea may not be entirely superfluous. Sampling will become still more important as data accumulate in sufficient amounts to warrant statistical studies.

The burden of these remarks is that students of ore deposition have a great deal to learn from studies of isotopes which should be encouraged in every possible way. At the same time, geologists need not be overawed by the mysteries of a new technique to the extent of accepting its first implications as infallible gospel. It will be better to withhold final conclusions until a more complete and accurate sampling, together with experimental work, has shown what methods of fractionation are possible and impossible.

H. E. McKinstry,

Department of Geology,
Harvard University,
Cambridge, Mass.,
Dec. 5, 1956

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ETHICS AND CONDUCT

Sir: The communication by Dean Charles F. Park, Jr., in the September–October issue of Economic Geology is excellent. Certainly, any improvement in standards of conduct must start at the colleges and universities.

I do feel that Dean Park's admonition of "land grabs" deserves some elaboration. Such a term can be applied too easily by a bad loser in a race involving mineral-right acquisition and/or geologic thought.

The exploration man, in established mining exploration organizations, is usually a mining geologist—a field which applies to only part of his duties. He is often a specialist in mineral-right acquisition. This field involves land-status determination and subsequent appropriate action to acquire mineral rights. In competition with others, he may not always win, but he is expected to wage a good fight to acquire (grab?) mineral rights.

It would seem that proper conduct would demand only that he maintain strict organizational loyalties and wage a clean fight. When is mineral-right acquisition clean? This question has confused many; I have no clear answer. I would certainly like to see some discussion of this question by men of stature and by others.

On Federal public domain, for instance, mineral rights are often acquired by location of mining claims. In such cases, the minerals are owned by the Government but can be acquired by individuals or organizations, providing they take certain legal steps. Until these steps are complied with, the ground is open to others.

I have felt that open ground is open ground, and that in a land race, one should play to win. Is this view unethical?

Thomas W. Mitcham

P. O. Box 1414,
Flagstaff, Arizona,
Oct. 11, 1956

TO TEACHERS OF GEOLOGY; THE MINING EXPLORATION MAN, HIS ETHICS—A PROFESSIONAL CHALLENGE

Sir: In dealing with the important question of ethics in geologic practice, as in the very useful communications recently published in this journal by C. F. Park, Jr. (Vol. 51, no. 6, p. 596–598, 1956) and by T. W. Mitcham (Vol. 51, no. 6, p. 599–601, 1956), it is doubtless difficult to codify a certain subtler but yet very real infringement of good ethics that approaches slander or libel of the work of others. Yet geologists who wish to be sedulous guardians of high ethical standards, especially as related to the commercial aspects of their duties, may well give heed to the meticulous observance of some basic rules of conduct on this score as well, particularly in openly evaluating the work or reputation of others.

Before expressing his criticisms, the conscientious geologist of high ethical standards, engaged in work of either scientific or commercial significance, should ask himself such questions as the following: Am I fully cognizant of the nature of the assignment or the limitations imposed upon the work that I am tempted to criticize? Has my own superficially similar duty really been comparable to that which I am appraising? Are my privately expressed judgments so phrased that the reader or hearer will have a comprehension of the differences between my own studies and the work commented upon? Is the section available for my critical comment distorted by being separated from its context? Is it true that the facts that can be marshalled are subject to only one interpretation—my own? Such questions, if thoughtfully raised, may modify a judgment which, given with the best of motivations but perhaps prematurely, might impugn the work of other honest and capable men wrongly and irreparably.

Slander can easily be committed by the most sincere of scientists if he wilfully neglects these considerations. Government men are in danger of making such errors about their colleagues or others because the nature and object of their studies is necessarily generally different from that of the company employee or consultant; this statement holds in reverse as well, and for the same reason, and it should impose the same caution. The element of special danger is that oral or even written comments, like charges of disloyalty, if given in private, can seldom be effectively refuted, no matter how little justified, because accuser, accused, and hearer are not in direct and mutual communication. The damage from such unintentional slander operates, no matter how ill-founded the accusation. Ultimately, the only ethical practice in evaluating the work of others is to show the same scrupulous regard for the rights of colleagues as for one's own!

CHAS. H. BEHRE, JR.

COLUMBIA UNIVERSITY,
NEW YORK CITY,
Dec. 3, 1956

GEOLOGY AND ORE DEPOSITS OF QUIRUVILCA, PERU

Sir: The carefully prepared exposition on the Quiruvilca (Perú) ore deposits by R. W. Lewis, Jr. (ECON. GEOL., vol. 51, p. 41–63, 1956) has contributed to our understanding of the geology of northern Perú. As with many

operating mines, the continued exploration and development of the ore bodies allows greater appreciation of the old features, and often uncovers new ones. Active geologic field work, largely by the present junior writer, has paced exploration. Of particular interest to geologists in general is our interpretation of the possible relationships of certain local features to regional geology, especially mountain building processes.

We have found three sets of vein structures existing in the district (1) the main veins, striking N 65° E and dipping 80° SE, (2) minor veins, striking N 40° E and dipping 70° SE, and (3) vein-faults, striking E–W and dipping vertically. The direction of movement is indicated by striations on the vein walls as well as the numerous minor splits into the walls (see Fig. 1).

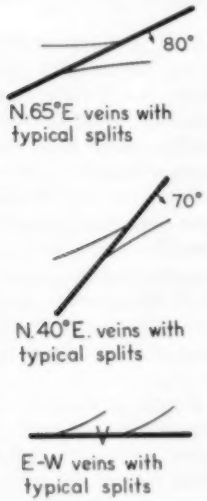

FIG. 1.

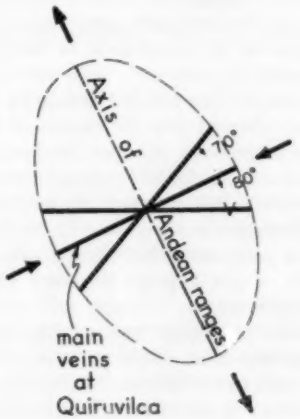

FIG. 2.

Now the general trend of the Andean mountain chain in northern Perú is about N 25° W. Casual spot observations indicate that the folding has a general apial trend of N 25° W and that thrust faults dip westerly. Figure 2 shows that Quiruvilca vein-fault structures superimposed on the trend of the Andean mountain ranges, giving the classic strained ellipsoid relations (see Fig. 2). It does not seem to us that this relationship is merely coincidental. A closer measurement of the age of mineralization is also possible.

Likewise of general interest is the presence of tourmaline. The mineral has ben found scattered throughout the district and appears to have formed over a wide time interval. Tourmaline may occur in more mineral deposits than previously reported because it is easily overlooked.

L. P. ENTWISTLE
V. F. HOLLISTER

LIMA, PERU,
Aug. 20, 1956

Note: The above discussion was published in Vol. 52, No. 1, and the accompanying figures were inadvertently omitted.

EDITOR

REVIEWS

Kohle, Naturgeschichte eines Rohstoffes. By W. E. PETRASCHECK. Pp. 104; figs. 64; 7½ × 5. Verständliche Wissenschaft, vol. 59. Springer, Berlin, Göttingen, and Heidelberg. 1956. Price DM 7.80.

This little well-printed book on coal by one of the foremost Austrian geologists is a very satisfactory summary for the general reader of the geology of bituminous and brown coals. This is the 59th of a series of similar primers on scientific subjects but is the second to have been prepared on coal. The first, now out of print, was written by Prof. K. A. Jurasky and was published in 1940. In his introduction Prof. Petrascheck points out that the considerable advances made in the understanding of coal geology since 1940 made necessary a completely new presentation of the subject. The primer covers very succinctly but rather comprehensively the general aspects of the geology of coal except coal microscopy and petrology. There is a short table at the end showing the world reserves in bituminous and brown coal, and a bibliography of about 20 titles by European authors exclusively. The book is recommended as an important addition to the small list of educational publications relating to the general subject of coal geology. It is hoped than an English language edition will eventually be forthcoming.

GILBERT H. CADY

URBANA, ILLINOIS,
Jan. 2, 1957

The Distribution of Mineral Products Throughout the World. Annales des Mines, November, 1956. Pp. 106, 11 diagrams, and many tables. 40 Rue du Colisée, Paris. Price, 600 frs.

Recent world events have indicated that the whole world economy can be hampered by the shortage of a particular mineral such as oil. As M. André Siegfried points out in his foreword to the important study of Mm. Blondel and Ventura relating to the "Distribution of Mineral Products throughout the World," mankind has entered a new era, for which "Mineral Age" would be a suitable name, and also a new period of this era that can be called "Oil period", which has just replaced the "Coal period." Since 1953, for the first time in the records of mineral economy, oil takes the lead in mineral production, its value having passed beyond the value of coal production.

The value of world mineral production does not exceed 5 per cent of the world's total national income but its products are "key-minerals," without which modern industrial civilization cannot live. What is the distribution of this value according to the products involved? How do the various countries rank according to the value of their mineral production? What are the existing relations between this production and national income? What are the geographical concentrations of the various minerals? How did mineral production evolve during the past? Such are the questions to which the study by Mm. Blondel and Ventura gives answers supported by a statistical documentation as comprehensive as possible. All those who wish to become acquainted more clearly with the world's mineral economy should be interested in this article.

Science and Economic Development: New Patterns of Living. By RICHARD L. MEIER. Pp. 247; tbls. 22; figs. 28. Technology Press of Massachusetts Institute of Technology and John Wiley & Sons, Inc., New York.

This imaginative book deals with the Present World Predicament, New Foods, New Fuels, and New Patterns of Living. It is a sociological approach to new economic development shaped by post-war discoveries in science and technology; well written, stimulating.

Geology and Mineral Resources of Japan. Edited by TSUKASA MURAKOSHI AND KATSUMI HASHIMOTO. Pp. 266. Geological Survey of Japan, Tokyo, 1956.

This volume is a summary of the geology and mineral resources of Japan, which it was planned to publish in 1953, accompanying the Geological Map of Japan on a scale of 1:3,000,000. This volume brings up to date a former summary entitled "The Geology and Mineral Resources of the Japanese Empire," published in 1926.

The volume is divided into two parts. Part I is the General Geology, which takes up the sedimentary formations of the Paleozoic, Mesozoic, Cenozoic, and Neogene. Chapter II of this part deals with the Igneous and Metamorphic rocks, both plutonic and volcanic, along with metamorphosed sediments. Chapter III takes up hot springs and earthquakes.

The portion on earthquakes deals with recent crustal movements as well as the quakes.

Part II consists of mineral resources with six chapters. Chapter I is entitled the "Metallogenetic Epochs and Provinces of Japan" with Precambrian and late Paleozoic to early Mesozoic mineralization. Another epoch deals with the late Mesozoic to early Tertiary mineralization. A third deals with late Tertiary mineralization; and a fourth, with Quaternary mineralization. Chapter II is entitled "Metallic Minerals," and each of the many minerals found in Japan is considered alphabetically. Chapter III is "Nonmetallic Minerals," of which there are a large number. Chapter IV gives the coal resources of Hokkaido, Honshu, and Shikoku. Chapter V is "Petroleum Resources," of which there are not many. Chapter VI deals with natural gas, of which a new gas field has been found in Japan.

In the back is a general map of Japan for locating the localities of the individual mineral deposits.

The work is a result of the efforts of many members of the Geological Survey of Japan and has been rather skillfully edited and quite well translated into English. It should serve as a good reference for the mineral deposits of Japan.

A Collection of Petrological, Mineralogical, and Geological Papers. Commemorative Volume dedicated to Dr. Seitaro Tsuboi. Tokyo, 1955 (1956).

This thick volume is dedicated to Dr. Tsuboi in celebration of his sixtieth birthday held in 1953, by his pupils and colleagues. Dr. Tsuboi has long been Professor of Petrology at the University of Tokyo, and he has a great many enthusiastic and admiring students. The preparation and editing was done by the following: Teiichi Ito, Teiroku Sueno, Takeo Watanabe, Hisashi Kuno and Shuichi Iwao.

After a foreward and a preface of the academic career and scientific work of Professor Tsuboi, the contents are divided into two parts. Part I consists of papers published in the Journal of the Faculty of Science, University of Tokyo, Section II, Vol. 9, Part II. This consists of thirteen papers prepared especially for the celebration. The papers deal with mineralogy, tectonic history, Paleozoic marine stratigraphy, Pleistocene-Pliocene boundaries, zonal arrangement of residual clays and chemical composition of lavas. Part II consists of papers published in

other journals mainly during the year 1954. This group of papers, which number twenty-one, consist of investigations dealing with the petrology of plutonic and volcanic rocks, mineralogical investigations of various minerals including the clay minerals, metamorphism, some structural geology, some aerial geology, and one paper on 1950–51 volcanic eruptions. This group also are written in English. The book as a whole is very nicely prited on good paper and includes many fine plates and other illustrations. It will serve as an excellent reference to students of petrology and mineralogy and should be contained in every petrologic laboratory. The students and colleagues of Doctor Tsuboi are to be congratulated in getting out such an excellent volume.

BOOKS RECEIVED

V. RAMA MURTHY

Géochimie des Eaux Souterraines. H. SCHOELLER. Pp. 213; figs. 48. Société Éditions, Paris, 1956. *Many ideas on the nature of oil-field waters, long considered as dogma, are challenged or restudied in this work. Several processes like dissolution, precipitation, base exchange, reduction of sulphate, concentration, are considered as the main agents of chemical, physical and dynamic equilibrium of waters. Also, a detailed study of trace elements in water is made. Effort is made to distinguish the oil-field waters from underground-water, surface-water and sea-water on a chemical basis. If not the first, this book is a valuable contribution to the geochemistry of waters associated with oil deposits.*

Geological History of the Netherlands. H. D. M. BURCK, L. A. Æ. VAN EERDE, H. M. HARSVELDT, and others. Pp. 147; pls. 16; figs. 67. Government Printing and Publishing Office, The Hague, 1956. *Geologic monograph intended as an explanatory text for the recently published 1: 200,000 geologic map of the Netherlands. Mostly stratigraphic details of rocks from Paleozoic to Cenozoic, with emphasis on early Cenozoic rocks. A small chapter on tectonics is included. Economic resources are solely non-metallic: coal, evaporites, oil and building stones of several types. Text is illustrated with excellent photographs, diagrams and paleogeographic maps, stratigraphic and columnar sections. This book is recommended on two counts: it will serve as an excellent reference text for a quick introduction in English to Dutch geology; in clarity of style and format it is a paragon for authors and publishers.*

An Encyclopaedia of the Iron and Steel Industry. A. K. OSBORNE. Pp. 558; pls. 16; figs. 9. Price, $25.00. Philosophical Library, Inc., New York, 1956.

Minerals Yearbook. STAFF OF BUREAU OF MINES. Pp. 1373. Price $4.50. U. S. Govt. Printing Office, Washington, 1956. *Volume I of three volumes. Chapters on mineral commodities, both metals and nonmetals, but exclusive of the mineral fuels. Included also are a chapter reviewing these mineral industries, a statistical summary, and chapters on mining technology, metallurgical technology, trends in technology and operations, and employment and injuries.*

Administration Report of the Government Mineralogist for 1955. Part IV, Education, Science and Art. L. J. D. FERNANDO. Pp. 19. Price, 50 cts. Government Publications Bureau, Colombo, Ceylon, 1956.

Topography, Geology and Iron-ore Deposits of the District East of Aswan. M. I. ATTIA. Pp. 262; pls. 98; figs. 1. Geologic Survey of Egypt, Cairo, 1955.

Bulletin de la Direction des Mines et de la Géologie. Gouvernement Général de l'Afrique Équatoriale Française. Pp. 110; pls. 16; tbls. 2. Service Geologique, Cameroun, 1956.

Die Gattung Palmatolepis. K. J. MÜLLER. Pp. 68; pls. 11; fig. 1; tbls. 2. Gedruckt mit Unterstützung der Deutschen Forschungsgemeinschaft, Frankfurt am Main, 1956.

Some Applications of Geophysical Methods to Geological Problems in the Gold Coast. L. O. GAY and M. KOSTEN. Gold Coast Geological Survey Bull. No. 21. Pp. 37; pls. 2; figs. 30. Price 9 sh. Geological Survey of the Gold Coast, Accra, 1956. *Collection of geophysical investigations made in the past few years. Need for using all available geologic evidence to interpret the geophysical data is stressed.*

Laurium. G. P. MARINOS and W. E. PETRASCHECK. Pp. 247; figs. 67 (Geologic and mining maps in pocket). Institute for Geology and Subsurface Research, Athens, 1956. *Geological Study of Laurium, Greece, with emphasis on mineral deposits and mining. Text in Greek, but a short summary in English is given.*

Il Centro Di Studi per la Preparazione dei Minerali. LUIGI USONI. Pp. 27; pls. 21. Consiglio Nazionale delle Ricerche, Rome, 1956.

Explanatory Text of the Geological Map of Japan. Kombumori (Kushiro-48). MASATORA KAWAI. Pp. 68; figs. 21; tbls. 16. Geological Survey of Japan, Hisamoto-cho, Kawasaki-shi, 1956. *Geologic map, scale 1: 50,000. Explanatory text in Japanese and English languages.*

Bulletin Geologique. Tome VIII–IX, 1954–1955. Pp. 252. Institut pour les recherches geologiques de la republique populaire de Croatie, Zagreb, 1956.

Lagerstatten und Lagerstattenbildung in Jugoslavien. ARNOLD CISSARZ. Pp. 152; tbls. 27; geologic map 1:750,000. Memoires du Service Geologique et Geophysique de la R. P. de Serbie, Beograd, 1956.

Zur Petrographie und Genesis sudwestmazedonischer Eisensilikatlagerstatten. ARNOLD CISSARZ. Pp. 261–340; pls. 8; fig. 1; tbls. 11. Bulletin du Service Geologique et Geophysique de la R. P. de Serbie, Beograd, 1954.

Petrology of the Nodaway Underclay (Pennsylvania), Kansas. N. J. MCMILLAN. Pp. 191–249; pls. 4; figs. 10; tbls. 5. State Geological Survey of Kansas, Bull. 119, pt. 6, Lawrence, 1956. *Detailed mechanical, chemical, x-ray analyses, and microscopic study of the very fine sand and underclay of the Nodaway coal in Kansas.*

Geology of the MacBride Lake Area Granville Lake Mining Division Manitoba. L. C. KILBURN. Pp. 24; tbl. 1. Manitoba Department of Mines and Natural Resources, Winnipeg, 1956. *Geologic map, 2 in. = 1 mile, and a descriptive accompanying text.*

Geology of the North Unit Theodore Roosevelt National Memorial Park. W. M. LAIRD. Pp. 27; pls. 21; figs. 9; tbl. 1. North Dakota Geological Survey, Grand Forks, 1956.

Coal Resources of the Upper Part of the Allegheny Formation in Ohio. R. A. BRANT. Pp. 68; figs. 19; tbls. 52. Price, 50 cts. Ohio Division of Geological Survey, Columbus, 1956. *Original estimated reserves of coal in the Upper Allegheny formation amount to 16,410,647,000 short tons, and about 80% of these reserves are in beds of thickness greater than 28 inches.*

Estudos, Notas e Trabalhos do Servico de Fomento Mineiro. Vol. XI, Fascs. 1–2. M. A. B. DA CUNHA LIMA, F. S. CARNEIRO, N. A. MURIAS DE QUEIROS, and others. Pp. 118. Ministerio da Economia Direccao-Geral de Minas e Servicos Geologicos, Republica Portuguesa, 1956.

Communicacoes dos Servicos Geologicos de Portugal. Tomo XXXVI. CARLOS TEIXEIRA, O. DA VEIGA FERREIRA, GEORGES ZBYSZEWSKI, and others. Pp. 257. Servicos Geologicos de Portugal, Lisbon, 1955.

Lexico Estratigrafico de Venezuela. Publicacion Especial No. 1. Pp. 729. Ministerio de Minas e Hidrocarburos, Caracas, 1956. *Index map and geologic map, scale 1: 4,000,000.*

Australia Bureau of Mineral Resources, Geology and Geophysics, 1955–56.

Bull. 27. The Geology of the Ord-Victoria Region, Northern Australia. D. M. TRAVES. Pp. 133; pls. 3; figs. 34; tbls. 2. *Results of reconnaissance geologic work in an area of over 70,000 square miles is given. Mineral production of the Kimberly Field, hydrologic investigation and petroleum prospects are discussed.*

Bull. 25. The Giralia and Marrilla Anticlines North West Division Western Australia. M. A. CONDON, D. JOHNSTONE, C. E. PRICHARD and M. H. JOHNSTONE. Pp. 86; pls. 7; figs. 14. *The Giralia and Marnilla anticlines are asymmetrical folds in late Mesozoic and early Cenozoic sediments. The anticlines were folded at four different periods.*

Rept. 18. Petrology and Petrography of Limestones from the Fitzroy Basin, Western Australia. J. E. GLOVER. Pp. 12; figs. 15.

Rept. 22. Oil in Glauconitic Sandstone at Lakes Entrance, Victoria. R. F. THYER and L. C. NOAKES. Pp. 92; pls. 2; figs. 8; tbls. 5.

Rept. 20. Micropalaeontological Investigations in the Bureau of Mineral Resources, Geology and Geophysics, 1927–52. IRENE CRESPIN. Pp. 77.

The Australian Mineral Industry—Quarterly Review and Quarterly Statistics. Vol. 9, No. 2. Pp. 51. Price, 3 sh. *Itemized statement of reserves, production and other statistics. Discussion of factors affecting mining investment.*

The Australian Mineral Industry, 1955 Review. Pp. 216. Price, 12 sh. *Production data and other statistics for 1955.*

California Department of Natural Resources—San Francisco, 1956.

California Journal of Mines and Geology. Vol. 52, No. 4. Pp. 301–665; pls. 9–11; figs. 9. Price, $1.00.

Bull. 174. Pumice, Pumicite, and Volcanic Cinders in California. C. W. CHESTERMAN. **Technology of Pumice, Pumicite, and Volcanic Cinders.** F. S. SCHMIDT. Pp. 119; pls. 4; figs. 107. Price, $2.50. *Pumice, pumicite and volcanic cinders are important natural resources of California and this bulletin is an exhaustive study of the mode occurrence, distribution, etc.*

Bull. 173. Minerals of California. JOSEPH MURDOCH and R. W. WEBB. Pp. 452; figs. 4. Price, $3.00. *Most complete and up-to-date information on the occurrence of minerals in California. Minerals are alphabetically arranged, and extensive references and cross references can give a wealth of information for the interested person. A very exhaustive bibliography of publications related to mineral occurrences in California is included.*

Illinois Geological Survey—Urbana, 1956.

Circ. 223. Relation Between Earth Resistivity and Glacial Deposits Near Shelbyville, Illinois. J. E. HACKETT. Pp. 19; pl. 1; figs. 3; tbls. 1. *Earth resistivity zones are closely related to glacial features near Shelbyville, Illinois. Limitations of this geophysical method to detect water-yielding deposits are discussed.*

Rept. of Inv. 197. Igneous Intrusive Rocks in Illinois and Their Economic Significance. K. E. CLEGG and J. C. BRADBURY. Pp. 19; pls. 6; figs. 1; tbls. 1. *Igneous rocks occur as dikes, sills, structures thought to be diatremes, and domes. Once the form of the body is known, the knowledge can be used in planning future mining operations. The quantity of coal spoiled by the igneous rocks is usually small.*

Rept. of Inv. 198. Farmdale Drift in Northwestern Illinois. P. R. SHAFFER. Pp. 25; pls. 2; figs. 3. *The Wisconsin age of the Farmdale drift is indicated by its lack of thorough dissection, its lack of evidence of continued exposure during sangamon interglacial time and its stratigraphic relationships with Iowan or pro-Shelbyville loess and Shelbyville till.*

Service Geologique de Madagascar—1956.

Carte Miniere et des Indices de Madagascar. HENRI BESAIRIE. *Mineral map of Madagascar, scale, 1: 500,000.*

Carte Geologique de Madagascar. HENRI BESAIRIE. *Geologic map of Madagascar, scale, 1: 500,000.*

Missouri Geological Survey—Rolla, 1956.

Geology of Missouri 1945–1955. E. L. CLARK, N. L. SCOFIELD, and J. W. KOENIG. Pp. 143.

Fifth Biennial Rept., Geological Survey and Water Resources Division. T. R. BEVERIDGE. Pp. 34.

Ontario Department of Mines—Toronto, 1956.

Sixty-fourth Annual Rept., Vol. LXIV, Pt. 6, 1955. Geology of Lount Township. J. SATTERLY. Pp. 46; pls. 13; figs. 6. *Geologic report with geologic map of the area, scale 1 inch to ½ mile.*

Sixty-fourth Annual Rept., Vol. LXIV, Pt. 8, 1955. Geology of Dungannon and Mayo Townships. D. F. HEWITT and W. JAMES. Pp. 65; pls. 17; figs. 9. *Geologic report with geologic map, scale 1 inch to ½ mile.*

Quebec Department of Mines—1956.

Geological Rept. 67. Trente-et-un-Milles Lake Area Electoral Districts of Papineau, Labelle and Gatineau. E. AUBERT DE LA RUE. Pp. 27; pls. 8. *Geologic report with geologic map (1: 63,360).*

Geological Rept. 70. New Carlisle Map-Area Electoral District of Bonaventure. P. C. BAGDLEY. Pp. 36; pls. 6; fig. 1. *Geologic report with geologic map (1: 63,360) and columnar sections.*

U. S. Geological Survey—Washington, D. C., 1956.

Prof. Paper 274-G. Ecology of Foraminifera in Northeastern Gulf of Mexico. O. L. BANDY. Pp. 179–203; pls. 29–31; figs. 25–28; charts 7; tbls. 4. *Frequency studies of foraminifera in the northeastern part of the Gulf of Mexico reveal basic uniform patterns of distribution. Paleoecological implications of these patterns are discussed. Depth-to-temperature relationships are demonstrated for some formations from the Miocene, Pliocene and Pleistocene of Florida.*

Prof. Paper 281. General Geology of Central Cochise County Arizona. JAMES GILLULY. Pp. 165; pls. 13; figs. 9. *A very thorough geologic study of the area.*

Prof. Paper 286. Age and Correlation of the Chattanooga Shale and the Maury Formation. W. H. HASS. Pp. 47; pls. 5; fig. 1; tbls. 8. *Detailed stratigraphic study of Chattanooga shale and Maury formation. The Chattanooga shale is considered to be of Late Devonian age, and the Maury formation is considered to be Mississippian, based on a study of the conodonts in 325 collections from 65 measured sections.*

Prof. Paper 305-A. Core Tests and Test Wells Oumalik Area, Alaska. F. M. ROBINSON. Pp. 69; pls. 6; figs. 6. Price, $1.75. *Test wells and core tests in the Oumalik area, Alaska, primarily for stratigraphic and logistic studies. Oil and gas shows were negligible and of no present commercial value.*

Bull. 1021-J. The Problem of the Cochrane in Late Pleistocene Chronology. T. N. V. KARLSTROM. Pp. 303–331; pl. 1; figs. 55–56. Price, 30 cts. *Radiocarbon dates on samples from Cochrane drift, Ontario, indicate that the area has been under ice cover from before 36,000 to some time before 4500 B.C.; the implication of these dates are discussed.*

Bull. 1028-F. Geology and Petrology of the Pribilof Islands Alaska. T. F. W. BARTH. Pp. 101–160; pls. 20–21; figs. 17–36; tbls. 1–7. Price, 60 cts. *Petrologic study of the alkalic rocks of the islands. The alkalic nature of the rocks is probably related to the great constant instability of the area.*

Bull. 1030-B. Stratigraphy of Parts of De Soto and Hardee Counties Florida. M. H. BERGENDAHL. Pp. 65–67; pls. 4; figs. 6–11.

Bull. 1030-H. Uranium in Black Shale Deposits, Northern Rocky Mountains and Great Plains. W. J. MAPEL. Pp. 211–235; pls. 14–15; figs. 51–54; tbls. 3. Price, 55 cts. *Uranium content of several shale beds in parts of Montana, North Dakota, Utah, Idaho and Oregon are given.*

Bull. 1030-J. Stratigraphy of the Morrison Formation in Part of Northwestern New Mexico. V. L. FREEMAN and L. S. HILPERT. Pp. 309–320; figs. 58–61. Price, 15 cts. *Revision of the stratigraphy of Morrison formation in the Laguna area of northwestern New Mexico.*

Bull. 1036-I. Colorimetric Determinations of Traces of Bismuth in Rocks. F. N. WARD and H. E. CROWE. Pp. 173–178. Price, 15 cts. *A rapid chemical method for determination of traces of Bismuth in rocks is devised and discussed.*

Bull. 1042-C. Geology of the Virginia City Quadrangle, Nevada. G. A. THOMPSON. Pp. 45–77; pl. 1. Price, 65 cts. *Study of stratigraphy, structure, petrology and economic geology of the area.*

Bull. 1046-B. Rare-Earth-Bearing Apatite at Mineville, Essex County, New York. F. A. MCKEOWN and HARRY KLEMIC. Pp. 9–23; figs. 5–10; tbls 3. Price 20 cts. *Association of rare earths, thorium and uranium in flourapatite.*

Bull. 1048-C. Geophysical Abstracts 166 July–September 1956. M. C. RABBITT, D. B. VITALIANO, S. T. VESSELOWSKY, and others. Pp. 193–289. Price, 25 cts.

Water-Supply Paper 1330-C. Water Requirements of the Aluminum Industry. H. L. CONKLIN. Pp. 103–139; figs. 19–23; tbls. 11. Price, 20 cts.

Water-Supply Paper 1360-C. Geology and Occurrence of Ground Water in the Townsend Valley Montana. H. W. LORENZ and R. G. MCMURTREY. Pp. 171–289; pls. 19–20; figs. 29–40; tbls. 5. *A large reservoir of ground water underlies the valley. In the southern end of the valley, artesian water in the Tertiary beds is a possibility.*

Water-Supply Paper 1360-D. Water Resources of Bill Williams River Valley Near Alamo, Arizona. H. N. WOLCOTT, H. E. SKIBITZKE, and L. C. HALPENNY. Pp. 291–319; pl. 1; figs. 41–45; tbls. 5. Price, 45 cts. *The quantity of ground water stored in the alluvium along the Bill Williams River in the 6-mile reach between the confluence of the Big Sandy and Santa Maria Rivers was estimated to be about 100,000–150,000 acre-feet, but all of it cannot be withdrawn. Three alternatives are suggested to provide a constant water supply of 7½ cfs for the area.*

SCIENTIFIC NOTES AND NEWS

The Association of Engineers of l'Ecole de Liege celebrates in May the 100th anniversay of its scientific journal *La Revue Universelle des Mines.* They will hold an international congress on La Recherche Scientifique et L'Industrie. The subjects will be Coal, Chemistry, Electricity, Nuclear Energy, Civil Engineering, Metals and Minerals. The Journal is the oldest technical journal in Belgium and one of the oldest in the world. The meetings will take place at the University, May 6–8.

The Geological Institute of the Presidency College, Calcutta, held a Golden Jubilee Celebration on the 16th of January, 1957, presided over by Professor N. N. Chatterjee. Dr. W. D. West was the Guest-in-Chief.

B. Brewster Jennings, Chairman of the Board of Socony Mobil Oil Co., Inc., addressed the A.I.M.E. Annual Meeting in New Orleans on February 26th on "Mankind's Stake in Middle East Oil." His talk was given at an all-Institute meeting in the Roosevelt Hotel, in which the organization's three branches participated.

The II Cuban Petroleum Congress will be held in Havana May 5–11, 1957. There will be six sections of which No. 1 will be Geology, Geophysics and Geochemistry. Titles of papers and an abstract should be sent before March 1 to II Cuban Petroleum Congress, Edificio Habana 800, Havana, Cuba.

The Massachusetts Institute of Technology has established a laboratory of earth sciences under the direction of Professor H. G. Houghton, head of M.I.T.'s department of meteorology. It will attempt a new and integrated approach to experimental and theoretical investigations of man's environment: the atmosphere, the oceans, and the land masses between, including the interior of the solid earth. It is jointly sponsored by M.I.T.'s departments of geology and geophysics and of meteorology, and will become a research center for geologists, geophysicists, geochemists, meteorologists, and oceanographers.

Eugene Callaghan, formerly director of the New Mexico Bureau of Mines and Mineral Resources, has been appointed chief geologist in charge of exploration for Haile Mines, Inc., with field headquarters in Salt Lake City.

Dr. Yasuo Sato, assistant professor at Tokyo University and faculty member of the Earthquake Research Institute, is spending the winter term in research with Professor Frank Press at the Seismological Laboratory of the California Institute of Technology as an Alfred P. Sloan Foundation Fellow.

J. H. Melvin, State Geologist of Ohio since 1947, has been elected vice president—Operations of the Pennsylvania Drilling Co. of Pittsburgh.

Alan Blatchford, chief geologist of Clutha Development Ltd., recently visited the Guadalcanal Protectorate and spent a month at Gold Ridge inspecting the exposures made by costeaning operations.

The Guadalcanal Survey announce the discovery of a phosphate deposit on Bellona Island in the Solomons, an uplifted atoll on the edge of the Coral Sea,

about 100 miles south of Guadalcanal, and 1,000 miles from the Australian mainland. It has been surveyed and sampled by the senior geologist, J. C. Grover.

J. W. CONOLLY of Australia visited the Guadalcanal Protectorate and examined 100 miles of beach sands.

P. A. PUDSEY-DAWSON has returned to Guadacanal from leave in Britain and has taken charge of the Department.

Discovery of ilmenite has recently been made by geologists in the New Jersey Department of Conservation and Economic Development. The first analyses of the New Jersey deposit show an average ilmenite content approximately double that in deposits elsewhere in the United States. This new deposit is much more convenient to nearby plants manufacturing titanium pigments. The first discovery was made in South Jersey by F. J. Markewicz, who noted what appeared to be a relatively high percentage of dark-colored metallic minerals in an excavation. Informed of this, M. E. Johnson, State Geologist, immediately visited the area and assigned a second member of his staff, geologist Daniel G. Parrillo, to help Mr. Markewicz obtain samples from test borings along a belt 2 miles long and a half mile wide. Fourteen boreholes have been sunk to date and through the cooperation of the Bureau of Mineral Research, at Rutgers University, samples from three of these already have been run through the laboratory showing in one hole 3.95% heavy minerals of which ilmenite constitutes 60 to 70%. A second hole averaged 8.9%; a third hole averaged 3.05%.

VICTOR OPPENHEIM and G. O. BRISCOE, consultants in petroleum and mineral explorations, have opened offices at Mercantile Securities Bldg., Suite 1206, Dallas 1, Texas.

E. L. OHLE, geologist for the St. Joseph Leac Co. in Bonne Terre, Missouri, is teaching a course in Economic Geology at Washington University, St. Louis, during the spring term. During the past summer he spent two months as a member of a field party examining mineral deposits in Central Africa.

G. B. MOODY, consulting geologist, Berkeley, California, will become the 41st president of the American Association of Petroleum Geologists on April 4. Serving with Moody on the 1957–58 Executive Committee will be T. A. LINK, President, Cree Oil of Canada, Ltd., Calgary, Alberta, and Toronto, Ontario, as past-president, and three other newly elected officers: Vice-President, B. W. BEEBE, Vice-President and Director of Production, Keating Drilling Co., Oklahoma City, Oklahoma; secretary-treasurer, W. J. HILSEWECK, partner, Blackwood & Nichols, Dallas, Texas; and, as editor of the A.A.P.G. monthly Bulletin of petroleum geology, S. A. WENGERD, associate professor of geology, University of New Mexico, Albuquerque.

The NATIONAL SCIENCE FOUNDATION announced that it will accept proposals to support on an experimental basis about 15 In-Service Institutes for Secondary-School Teachers of Science and Mathematics to be held during the academic year 1957–58. Summer and academic-year institutes are presently operating in 111 colleges and universities throughout the Nation with support from the Foundation.

EARL IRVING, after eleven years in the Philippines, left on January 26 for the States. He is leaving the U. S. Geological Survey to join M. A. Hanna & Co. to direct exploration in Brazil. He has been chief of the Mining Division of the International Cooperation Administration, and its predecessors.

PAUL FOURMARIER has been awarded the Wollaston Medal by the Geological Society of London, in appreciation of his researches on rock structure, on the Belgian coalfields and on the economic geology of the Belgian Congo.

H. D. DINES has been awarded the Murchison Medal by the Geological Society of London, in recognition of his services to economic geology, particularly in reference to the metalliferous ore field of Cornwall and Devon.

E. J. LONGYEAR Co., consulting mining engineers and geologists, early this year completed their contract with the Portuguese Government for the reconnaissance mineral survey of 140,000 square kilometers in the provinces of Angola and Mozambique, Africa. The areas covered included three in Angola and two in Mozambique. The reports are in five volumes and the maps accompanying these reports comprise in total an area of almost two and one-half acres of cartography. These reports and maps are on file with the U. S. Geological Survey in Washington, D. C.

The Southeastern Section, Geological Society of America will hold a meeting at Morgantown, West Virginia, on May 16–18. The central theme will be "Economic Geology of the Southeastern United States in Relation to Recent World Events." Review papers will cover metals, industrial minerals, coal, petroleum, radioactive minerals, and water supply. On Friday there will be a symposium concerned with interpreting recent gravity and magnetic surveys by the U. S. Geological Survey in northwestern Virginia and eastern West Virginia. A Saturday field trip to the new Humphrey Mine and Beneficiation Plant of the Pittsburgh Consolidation Coal Co. at Morgantown will take place. Information on hotels and program may be obtained from the West Virginia Geological Survey, P. O. Box 879, Morgantown, West Virginia.

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PLEASE TAKE NOTICE

For "BOOKS IN GEOLOGICAL SCIENCES"—a list of current and standard books on geology and related fields—available for purchase thru Economic Geology Business Office, 105 Natural Resources Bldg., Urbana, Illinois, see back pages of the No. 1, or February, 1957 issue.

FIFTIETH ANNIVERSARY VOLUME

ECONOMIC GEOLOGY

1905–1955

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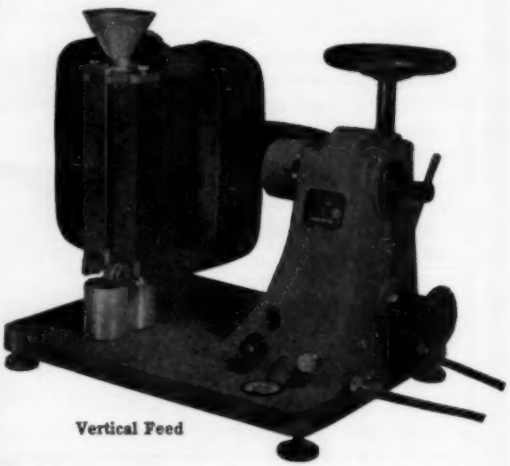

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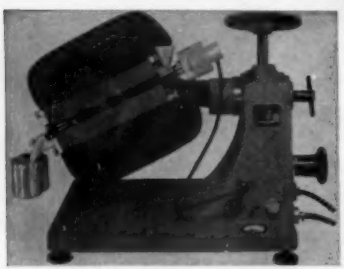

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